Psychological Implications for Submarine Display Design

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ABSTRACT

This paper addresses a number of psychological issues pertaining to display design. We review the literature comparing 3-D and 2-D displays and evaluate the findings in terms of sub-surface environments. In addition to the specific problem of display dimensionality this paper outlines a number of perceptual, cognitive and ecological factors that are relevant to display design for submarine environments. The Generative Transformational approach to visual perception is outlined and the relevance of transformational theory to display design is discussed. The paper also discusses a number of practical and theoretical factors relevant to empirical assessment of display utility and outlines three key areas for future research – representing uncertainty, using a cognitive model of human decision making, and conveying affective information - that have the potential to uncover novel theoretical developments and new technologies.

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Psychological Implications for Submarine Display Design

Executive Summary

It is widely anticipated that technological advancements in display design should lead to corresponding increases in situation awareness and improved task performance among display users. However, it should not be assumed that there is an immediate transfer from technological advancement to overall improvement. While designers are now capable of designing realistic, dynamic, and information rich displays, the information processing abilities of display users have remained static. If display designers fail to understand the abilities of the display users, then it is unlikely that the full potential of the new technologies can be realised. Against this background, the aim of this paper is to review psychological issues pertaining to display design.

The paper addresses perceptual factors such as colour perception and luminosity contrast, cognitive factors such as short- and long-term memory limitations and decision making heuristics, and ecological factors such as task requirements and information type and structure. This paper also reviews the literature regarding the use of two- and three-dimensional displays, and makes a number of suggestions in relation to display dimensionality in sub-surface environments. Additionally, the Generative Transformational Approach to visual perception is briefly outlined and its relevance of the theory to display design is discussed.

The paper discusses a number of practical and theoretical factors relevant to empirical assessment of display utility, such as the benefits and limitations of qualitative and quantitative research, and the competing pressures of internal and external validity. It is suggested that researchers adopt a strategy whereby initial, simple experiments based on well-replicated principles and involving semi-realistic tasks are carried out, the findings of which are then used to inform the design of subsequent, more complex and realistic experiments.

The need for further research in three key areas is identified from the literature review. It is suggested that research in these areas has the potential to uncover "game-changing" theoretical developments and new technologies. These areas are: the representation of different types of uncertainty, decision making aids, and the use of affective data.

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Contents

1. Introduction

Recent technological advances have seen a rise in computer information processing speed and increased sophistication in data visualisation. It is widely anticipated that incorporating these technological advancements into display design should lead to corresponding increases in situation awareness and improved task performance amongst display users. However, there is a degree of risk in assuming a one-to-one transfer between technological advancement and overall improvement. While designers are now capable of designing realistic, dynamic and information rich displays, the information processing abilities of display users are unchanged. Chalmers, Easter and Potter (2000) have suggested that faster computers may actually have a detrimental effect on task performance, as they can create a higher level of cognitive demand and information overload. In order to avoid this scenario, it is necessary to recognise the need for psychological insight into the problem.

Display design should be thought of in terms of human-computer interfacing. If the display and the display user are conceptualised as a system rather than as distinct entities, it becomes obvious that task performance is contingent upon the abilities and limitations of both units. If display designers fail to address the abilities of the display users, then it is unlikely that the full potential of the new technologies can be realised.

In light of these points this paper provides a review of the perceptual, cognitive and ecological factors that are relevant to display design for submarine environments. A current issue in display design is the relative utility of two-dimensional and three-dimensional visualisations. The majority of past research has focused on aeronautical and terrestrial applications. This paper reviews the literature and makes a number of suggestions regarding the use of two- and three-dimensional displays in sub-surface environments. Elsewhere, Vickers has outlined the Generative Transformational Approach to Visual Perception (Vickers, 2002). This paper briefly discusses the implications of Generative Transformational theory for display design. Finally, the paper also discusses a number of practical and theoretical factors relevant to empirical assessment of display utility, and outlines a number of future research directions.

2. Human Psychology and Display Utility

2.1 Perceptual Factors Influencing Display Utility

Perception can be thought of as a collective term for those processes that organise sensory input into meaningful patterns. It is important to note that there is not always a straightforward relationship between the physical nature of sensory input and the way that this input is perceived. For example, most people should be familiar with visual illusions similar to Figure 1, in which two lines appear to be of qualitatively different lengths despite being physically equal. Given that the human visual system is susceptible to illusory phenomena such as these, visual display design should be informed by knowledge of the capabilities of human perception. This section outlines a number of perceptual factors that may affect display utility.
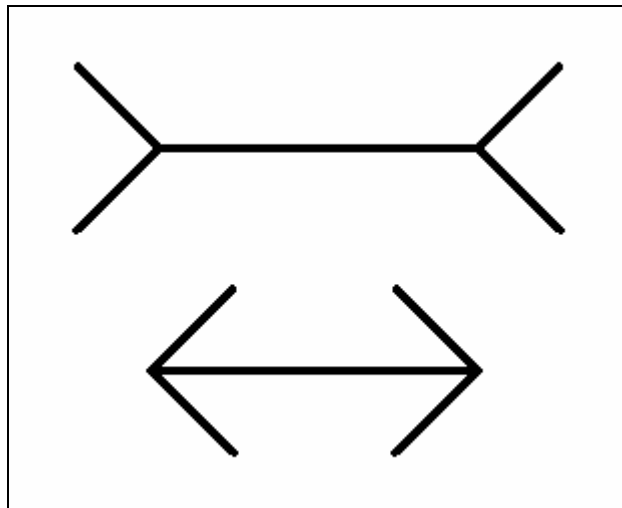
Figure 1: The Mueller-Lyer illusion, in which the upper horizontal line appears to be longer than the lower horizontal line, despite the fact that both lines are the same length

2.1.1 Achromatic effects

A number of researchers have demonstrated that the brightness of objects or areas is dependent upon the luminance of adjacent areas (Kingdom, 1997). For example, it has been demonstrated that two identical grey areas appear to be different in terms of brightness if one of the areas is presented on a black background and the other on a white background (Figure 2)(White, 1979). Figure 3 illustrates that this effect can also occur in more naturalistic settings. The light grey checked area that lies in shadow is in fact the same brightness as the dark grey checked area that is not in shadow. This has obvious implications for the use of grey scales to

convey information. For example, if grey-scaling is used to indicate the threat-status of target platforms, then a neutral or unspecified platform may be wrongly perceived as either a friend or enemy, depending upon the location of the platform on the display and the relative brightness of its background.
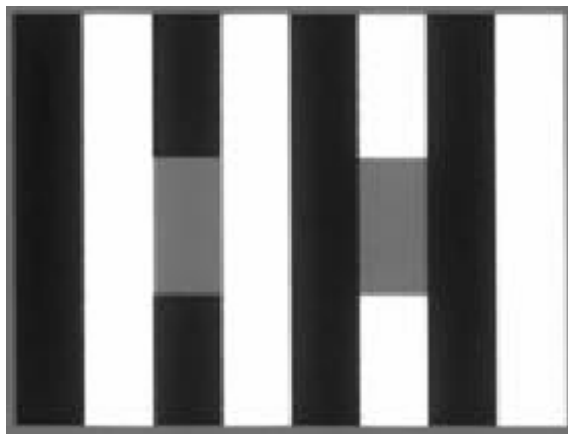
Figure 2.   Although the grey area on the white background appears to be darker than the grey area on the dark background, the two areas are actually of equal brightness
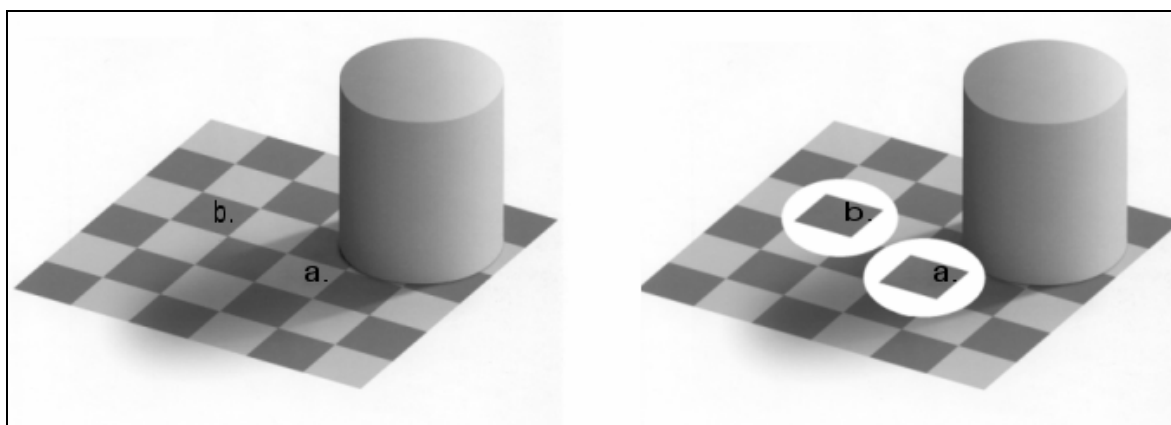
Figure 3. Despite appearances, the light grey check that lies in shadow (a) is actually of the same brightness as the dark checks that are not in shadow (b)

An alternative to using grey-scales for portraying information, sometimes used in graphical displays, is to use different patterns or crosshatching. However, display designers should be

aware of the possibility of creating Moire effects: areas of water- or silk-like shimmering that result from closely spaced lines (Figure 4) (Laisk, 1971). Moire effects can be distracting and may potentially cause fatigue. Display designers should also be aware of other illusory effects that can occur when lines or line segments are overlaid. For example, straight lines can appear to be curved when placed against a background of curved or radiating lines (Sanders & McCormick, 1993). This might be problematic in 3-D displays as it could distort depth perception.
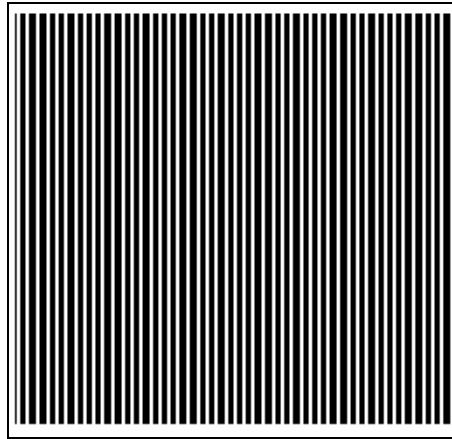
Figure 4.   Area of shimmering caused by a Moire effect

2.1.2 Colour perception

The use of colour within displays raises a number of potential perceptual problems. For example, a well-established body of data exists suggesting that red and blue should not be used next to each other within displays as they can cause a number of distracting effects (Kosslyn, 1994). One example of this is known as chromatic aberration: because of the difference in wavelength between red light and blue light, the eye is unable to focus on both colours at the same time. As a consequence of this, the colours will appear to shimmer as they move in and out of focus (Matthews & Mertins, 1989). In order to avoid chromatic aberration it is simply suggested that red and blue are not used in close proximity[1].

Another perceptual phenomenon associated with the use of red and blue within displays is chromostereopsis. In this case, when red and blue are simultaneously presented on a dark background the two colours will be perceived as being separated within the depth plane. Red will be seen as being closer to the viewer and blue as being further away (Matthews & Mertins, 1989). Similarly, Kosslyn indicates that warm coloured objects that are placed behind cool coloured objects will struggle to move into the foreground (Kosslyn, 1994). Both of these

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[1] This is interesting because red and blue appear together on many military displays representing hostile and friendly tracks.

effects are potentially distracting, and there is evidence to suggest that they may cause visual fatigue (Murch, 1984 cited in Helander, 1987). To avoid chromostereopsis it has been suggested that "colours should not be used in situations where less than 3.39' of disparity can be recognised" (McLain, Cacioppa, Reising, & Koubek, 1990).

There are a number of perceptual phenomena that should be considered when colour is to be used to convey quantitative or qualitative information. Individual colours are perceived as being different because they are comprised of a mixture of various light wavelengths. A number of factors may alter this mixture, thereby distorting the user's colour perception. For example, the ambient lighting of the environment in which a display is being viewed may alter the colour-mix: if the colour of the light in the display room changes from, say, white to red, then this will have an effect upon the colours on the display screen (Foley & Moray, 1987; Helander, 1987).

It should also be noted that colour perception in humans is almost entirely absent at low-light levels. The discrimination of the temporal frequency of visible light (yielding colour) is handled by what is termed the photopic system (utilising the response of cone cells). This system is not responsive in low-level light. At those lower light levels a scotopic system (primarily utilising rod sensitivity) becomes more useful. Scotopic vision (night vision) is virtually monochromatic (Coren, Ward & Enns, 1994). Hence, display components depending on colour discrimination (colour saturation) probably should be avoided for operations at very low-light levels.

Other effects that may cause colour distortion are simultaneous colour contrast and chromatic adaptation (Palmer, 1999). Simultaneous colour contrast occurs when the perception of a colour is influenced by the colours that surround it. Depending on the saturation of the colour and the time it is viewed for, the colour of an object will shift in hue toward the complementary hue of the background colour. Chromatic adaptation occurs after prolonged exposure to a specific colour. This will cause a reduction in sensitivity to that colour in the period immediately following (Palmer, 1999). For example, if the user is exposed to a blue 'loading' screen for a prolonged period they may subsequently be less sensitive to objects and symbols of that hue within the display.

Colour afterimages (Palmer, 1999) occur after viewing highly saturated colours for a prolonged period of time. Afterimages are the complementary hue of the original colour. For example, green objects have a red afterimage and black objects have a white afterimage. Individuals commonly experience monochromatic afterimages after staring at bright lights. The phenomenon may be a potential distraction similar to chromostereopsis or chromatic aberration. Designers should be mindful of this aspect of colour perception.

2.1.3 Blurring

Korge and Kreuger (1984, cited in Grandjean, 1987) investigated the effects of object blurring or sharpness upon accommodation, finding that observing blurred characters led to a shift in accommodation to the resting position. Bisantz, Kesevadas, Scott, Lee, Basapur, Bhide, Sharma & Roth (2002) have suggested the use of blurring to indicate uncertainty in track

position, heading and type within visual displays (Bisantz, Kesevadas, Scott, Lee, Basapur, Bhide, Sharma, & Roth, 2002) (Figure 5). To date there has been no empirical investigation of the usefulness of this technique, but given that there is a small amount of evidence to suggest that characters or objects that are blurred can cause fatigue and discomfort (Grandjean, 1987), sharpness should probably not be used as a coding device.
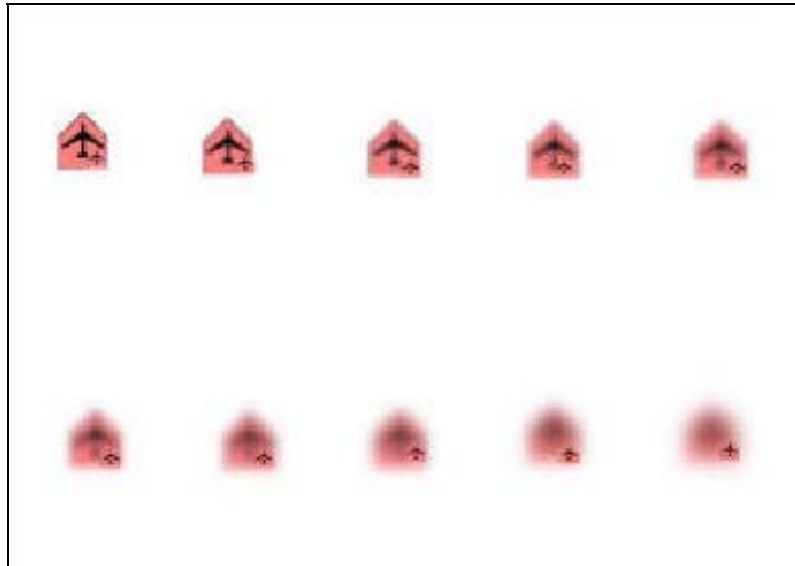
Figure 5.   The use of sharpness or blurring to convey uncertainty (Bisantz et al., 2002)

2.1.4 Perceptual Abnormalities

Colour-blindness affects an individual's ability to perceive or distinguish between colours. It has been estimated that colour-blindness occurs in 8% of the male population, and 1% of females (Kosslyn, 1994; Palmer, 1999), however there are a number of different forms of colour-blindness, and the severity of the effects can vary. The cause of colour perception abnormalities can be situated at either a retinal or cortical level. At a retinal level, normal human colour perception relies upon three types of photoreceptors: L-, M- and S-cones. L-cones are sensitive to long wavelength light frequencies, M-cones are middle wavelength sensitive, and S-cones are short wavelength sensitive. Colour-blind individuals are typically missing one or two of these types of cells, and the type and extent of an individual's perceptual deficit is contingent upon the type of cone cells that they are missing (Stockman & Sharp, 1998).

Individuals with the most common forms of retinal colour-blindness are missing (or malfunctioning) either L- or M-cones and therefore perceive red and green hues as shades of grey (Palmer, 1999). As a result of this they are unable to discriminate between red or green hues. Additionally, this deficit affects the discrimination of colours that differ in luminance

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according to the degree of green or red in its make-up (Helander, 1987), and also affects an individual's ability to distinguish between these two colours and greys of equal luminance. Less common forms of retinal colour-blindness include tritanopia and monochromatopia. Tritanopia affects the ability to discriminate yellows and blues. Tritanopic individuals experience these colours as shades of grey, and are therefore are subject to similar problems as red/green colour-blind individuals. Monochromats have only one type of colour photoreceptor cell (Stockman & Sharp, 1998) and therefore are only able to distinguish between variations in lightness, not between different colours.

Colour perception impairment can also result from cortical damage. Individuals with achromatopsia are unable to perceive any colour at all and see the world in black and white. This disorder can affect either all or part of their visual field. Other disorders arising from cortical damage can affect an individual's ability to recognize or name different colours (Kolb & Wishaw, 1999; Palmer, 1999). However, unlike retinal colour-blindness, which is a congenital disorder, cortical colour-blindness is usually the result of some form of brain injury.

The non-negligible proportion of colour-blind individuals in the population makes it necessary to either screen users for the condition, or design displays so that they do not require colour differentiation. However, any decision should bear in mind the relative ease with which colour-blindness can be detected, and the potential benefits and limitations of using colour to encode information (as outlined in sections 2.1.2 and 2.2.6).

A second form of perceptual abnormality that might potentially impact upon display utility is stereoblindness. Stereoblindness or stereoanomaly is the inability to perceive differences in depth when the viewer is presented with stimuli that vary in degree of stereoscopic disparity. It is estimated that 30% of the population exhibit errors in stereoscopic depth judgments, and around 3 to 10% of the population are stereoblind (Palmer, 1999; van Ee & Richards, 2002). This has obvious implications for the use of stereoscopically presented 3-D displays and is potentially a greater problem than colour-blindness for two reasons. First, it appears to affect a larger proportion of the population. Secondly, although visual displays can be designed so that users do not need to differentiate between colours it is difficult to envisage a way of making stereoscopic displays accessible to stereoanomalous individuals.

2.1.5 Perceptual Factors: Summary

This section outlined a number of perceptual factors that may influence display utility. These include:

- *Achromatic effects, such as contrast luminosity and moire effects.*

- *Chromatic (colour perception) effects that may be distracting such as chromatic aberration and chromostereopsis, and factors that may influence the ability to discriminate between two different colours such as simultaneous colour contrast, chromatic adaptation, and afterimages.*

- *The possibility of distraction due to blurring or image sharpness.*

- *The impact of two relatively common perceptual abnormalities (colour-blindness and stereoanomaly) upon display design.*

2.2 Cognitive Factors Influencing Display Utility

Cognition is a broad term that is used to describe processes that are directly related to, or involved in, thinking, conceiving and reasoning. Given that the aim of a visual display is to convey information, it is necessary to take human cognition into account when designing visual displays. This section outlines a number of cognitive factors that may affect display utility.

2.2.1 Attention

People have limited attention capabilities, in the sense that they can only pay attention to a limited amount of information at once and over a limited time (Endsley, 1995b). Sanders and McCormick (1993) identify three different types of attention that are relevant to display design, and outline several useful guidelines (Sanders & McCormick, 1993). Selective attention involves monitoring several sources of information to perform a task, and divided attention involves performing two or more tasks simultaneously. If display users are performing tasks involving selective or divided attention it is suggested that the different information sources be combined within a single display, rather than requiring users to monitor two or more separate displays. However, integrating displays may lead to higher levels of display clutter (Yeh & Wickens, 2001), and there is evidence to suggest that integrated displays may be more fatiguing, that is, operators will maintain maximum vigilance for a shorter period of time (Sauer, Wastell, Hockey, Crawshaw, Ishak, & Downing, 2002). Focused attention involves attending to one or more channels of information while avoiding being distracted by other information. It is suggested that displays being used for focused attention tasks should display only information that is related specifically to the task. Alternatively, if this is not possible, the display information could be subjected to intensity coding whereby salient information is made brighter, and less important or redundant information is faded (Yeh & Wickens, 2001).

2.2.2 Short-term memory limitations

Williges, Williges and Elkerton (1987) stress the need to minimize the amount of information that is held in working, or short-term memory (STM) by interface users, particularly if multiple tasks are being performed simultaneously (Williges, Williges, & Elkerton, 1987). It is widely accepted that the upper limit of STM is between 5 to 9 items (Miller, 1956), varying according to data complexity, presentation sequence, the length of time the information must be remembered for, and the amount of competing information.

Eddy, Kribs and Cowen (1999) list a number of common errors made by display users that can be associated with STM limitations. These include confusing and forgetting track numbers; confusing track kinematic data, such as approaching versus departing, or climbing versus descending; and combining past track-related events or actions with incorrect tracks and associating completed ownship actions with incorrect tracks. Errors such as these might possibly be minimized if information such as track heading and type are explicitly represented within the display, thereby reducing the amount of information needing to be stored in working memory.

Another area in which STM limitations may impact upon display utility is in the design of selection menus (Williges et al., 1987). Wickens (1984) indicates that if users need to consider all of the menu options simultaneously, the menu will be more effective if the number of items is less than or equal to the upper limit of STM (Wickens, 1984).

2.2.3 Long-term memory limitations

There is a growing body of research suggesting that the way objects are represented within a display may affect activities such as visual search, naming and identification (Smallman, Oonk, & St. John, 2001a; Smallman, Oonk, St. John, & Cowen, 2001b; Smallman et al., 2000; Smallman, Schiller, & Mitchell, 1999). Task demands generally require that information such as platform type (cruiser, carrier, submarine), and threat affiliation (friendly, hostile, neutral, unknown) be implicitly represented within displays. However, long-term memory (LTM) limitations place restrictions upon the number of different symbols that can be used to represent these data. It is commonly assumed that there is an upper limit to the number of different symbols a user can remember successfully, and that this is moderated by factors such as practice, familiarity, and stress-level (Helander, 1987). Helander provides an outline of the maximum and recommended number of featural differences that should be used for a range of coding dimensions, such as colours, geometric shapes and icons (Helander, 1987). According to Grether and Baker (1972 cited in Helander, 1987), in optimal conditions, with a high level of training and familiarity, and allowing a 5% error rate, subjects can differentiate between up to 15 different geometric shapes[2]. No error rate vs. number function is provided. However, to ensure a high level of accuracy in operational conditions five different shapes is the recommended limit.

LTM limitations also appear to be influenced by the number of dimensions used to encode information, the particular combination of dimensions that are used, and whether the dimensions are orthogonal or redundant (Sanders & McCormick, 1993). Heglin (1973 cited in Sanders and McCormick, 1993) suggests that no more than two dimensions should be combined if rapid interpretation is required, and also provides a list of dimensions that are not recommended to be used together. These include flash-rate and brightness, shape and letter or number, and colour hue and contrast.

Two main approaches have been used to represent objects within displays: realistic icons and abstract symbols. The use of realistic icons may be regarded as being advantageous because it is easy to differentiate between broad classes of objects. For example, the helicopter icon in Figure 6 is easily differentiated from the cruiser icon. However, research has indicated that users have difficulty distinguishing between icons within categories (Smallman et al.,

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[2] A reviewer has pointed out that this seems a very limited range of discrimination given that humans commonly deal with much larger geometric shape sets, such as the English alphabet, or idiographic languages. Language acquisition and its relation to the written word is a complex field beyond the scope of this brief report. Once again, the message for designers is that human memory and processes of discrimination have capacity limitations. These limitations vary dramatically, between experts and novices for example. Clearly, the simpler the task of discrimination of geographic shape in representing dimensions of a situation the better for rapid abstract information transfer.

2001b). For example, the cruiser and carrier icons in Figure 6 are visually similar and therefore potentially easy to confuse. In contrast to this, Figure 6 demonstrates there is no such restriction upon the potential differences between abstract symbols. Arbitrary coding, however, removes any potential advantage that may be provided by semantic associations between object type and dimensions such as shape. For example, boat shapes can be used to represent boats and not aircraft.

Smallman and colleagues (Smallman et al., 2001a; Smallman et al., 2001b) have suggested an alternative approach for representing objects within displays. They have developed a hybrid of realistic icons and abstract symbols that they call Symbicons. Some examples of Symbicons are displayed in Figure 6. Symbicons can be infinitely differentiated and yet retain features such as semantic shape associations that are believed to aid LTM information encoding and retrieval. The results of a visual search experiment indicated that Symbicons provided an advantage over both realistic icons and abstract symbols for speed and accuracy of categorization (Smallman et al., 2001b). The results of this study, in fact, were not statistically significant. The authors suggest that this may be because the number of different platform types used in the study was limited. However, we should be careful not to draw conclusions from this work until further research has been conducted in this area. Symbicons appear to lack some of the redundancy in coding features that is characteristic of typical abstract symbols (e.g. a naval symbol representing enemy vessel uses both colour and shape).
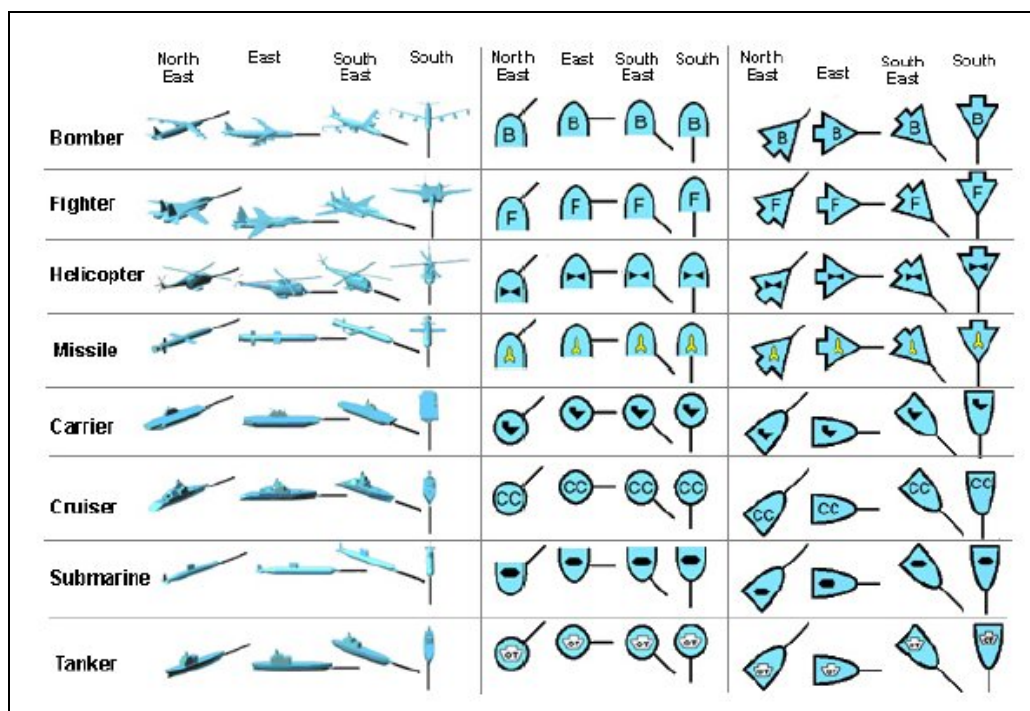
Figure 6. Examples of icons (left), symbols (center) and symbicons (right). From (Smallman et al., 2001b).

2.2.4 Decision making *heuristics* and *models*

Traditionally, human decision-making has been thought of as classically rational. In other words, it is assumed that when an individual makes a decision, they first search the environment for all salient information, attach some sort of weight to this information, and then weigh up the comparative utility of making each of the choices available to them. It is generally recognised that there are problems associated with the classically rational approach. First, it is extremely time consuming. Second, it assumes unlimited memory capacity. Third, empirical research suggests that people do not behave like this. Research indicates that humans rely heavily upon heuristics and biases when making decisions (Arkes & Hammond, 1986). Rather than weighing up all of the information that is available within a given environment, individuals appear to base decisions upon a limited number of salient cues Todd & Gigerenzer (1999).

The amount of information used to make a decision appears to be related to two factors: the cost of making a wrong decision, and the structure of information within the environment. Simple, low cost decisions appear to require less information than complex, high cost decisions (Lee & Cummins, submitted). However, in certain environments information is structured in such a way that it is not necessary to carry out exhaustive searches regardless of the importance of the decision. If the first piece of information is important enough, it may not matter what the weight of any subsequent cues are.

Research into threat cues indicates that certain cues appear to be more significant than others. For example, platform type, weapon envelope and electronic emissions were found to be the three most salient cues for threat assessment by experienced surface warfare navy officers (Liebhaber & Feher, 2002). Research may be able to determine the most important cues employed by display users across a range of the most frequent decision-making tasks. By explicitly representing only the most salient cues, it may be possible to reduce search time and display cluttering, and thereby reduce cognitive load. Additionally, it may be possible to develop simple algorithms capable of assessing conditional states such as threat status, which could then be used to alert display users of potential threats. Todd and Gigerenzer (1999) provide a number of fast and frugal heuristics that are capable of closely replicating human decision-making that may be suitable for such a process.

Another influential theory emerging in recent years has been so called, Naturalistic Decision-Making based on Klein's Recognition Primed Decision-making model. This argument holds that decision-making depends on the schematic representation of a "situation" as a mental model within a framework of cognitive schemata (Lipshitz & Ben Shaul, 1997). Such a decision process is shown Figure 7. Here, schemata mediate both information search and interpretation, helping the decision-maker quickly identify meaning. Consequently, accurate mental models (i.e. an understanding of 'reality' that accurately reflects important components of 'reality') are likely to be critical components of successful decision-making. Experts are able to recognise patterns and contingencies in a situation and decide very quickly.
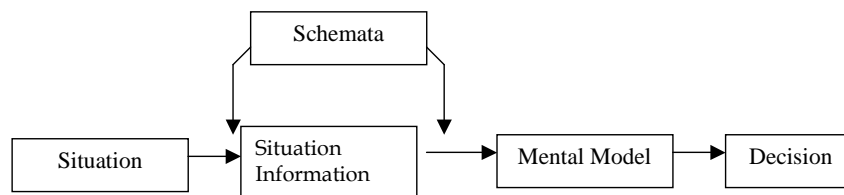
Figure 7. Lipshitz and Ben Shaul's Schemata-driven mental modelling component of Klein's RPD model

2.2.5 Gestalt grouping principles

According to Helander (Helander, 1987), display designers should be aware of Gestalt principles such as proximity and similarity when grouping display information. Viewers tend to perceive regions or objects of the same shape or colour as distinct groups or entities (Kosslyn, 1994). Additionally, objects that are enclosed within a region by a linear boundary are perceived as belonging together (Palmer, 1999). These principles can be used to inform display design so that information can be grouped in an immediately interpretable manner. For example, Wickens and Carswell (1995) suggest that if "similar information processing is required for distinct display elements, then increasing their spatial proximity or surrounding them with boundaries should improve performance" (Wickens & Carswell, 1995), and Brand and Orenstein (1998) have found empirical evidence supporting this.

Figure 8 displays an example of Gestalt grouping principles being applied to display design. The icons of functions that are closely related are situated in close proximity to each other and are enclosed within a common region. For example, the "print" and "print preview" icons are positioned next to each other within a region that is separate to the "new document", "open document" and "save document" icons. Additionally, it may be useful to use combinations of these principles to represent hierarchies of function similarities. One set might be organized horizontally, and another set of related functions organized vertically, with sub-groupings enclosed by linear boundaries.

Figure 8.   An example of Gestalt grouping principles being applied to display design. From the Microsoft Word toolbar.

2.2.6 Colour and Cognition

There are a number of cognitive factors that must be considered if colour is to be used in visual displays. Numerous sources indicate that display designers should take into account the semantic associations of colours (Helander, 1987; Kosslyn, 1994a). For example, colours are associated with certain objects or types. The sea is generally associated with the colours blue

or green, and therefore should not be depicted as red or yellow. Similarly, land should be depicted as either green or brown. By aligning the properties of the display with users expectations, search time and confusion can be minimized.

Colours are also associated with abstract concepts. For example red is often associated with danger, yellow with caution, and green with safety. A number of different colour coding schemes exist. The US Department of Defence military standards specify a colour coding scheme for use in visual displays in which red is used to indicate inoperative systems, flashing red indicates emergency situations, yellow advises caution, green indicates a fully operational system, and white represents transient conditions (Helander, 1987). Additionally, there is some evidence to suggest that colours may be associated with affective states. For example blue is associated with tranquillity, and orange with excitation (Grandjean, 1987; Norman & Scott, 1952). These associations may be of importance if colour is being used to convey information such as indicating possible areas for manoeuvring in order to maximize passive sonar readings. If red is used to indicate the best or optimal area because it is a sonar 'hotspot', it may cause confusion because red can also mean danger.

Another possible problem involves colour-scales being used to convey semantic information, (that is *meaning* as opposed to the lower level perceptual aspects discussed in 2.1.2). A number of sources stress that display designers should avoid using colour hue to indicate quantitative information because hue is not a psychological continuum (Kosslyn, 1994a). One way of conceptualising the relationships between different colours is in terms of physical properties. In this way they can be thought of as being arranged along a vertical scale, moving from red at a wavelength of 674 nm. through orange (651 to 600 nm.), yellow (584 nm.), green (504 nm.), and blue (472 nm.) to violet at 434 nm. However, multidimensional scaling of human subjects' colour similarity ratings has revealed that the mental representation of colour is more like a wheel or circle than a vertical scale (Shepard, 1962). In other words, red and violet (the ends of the visible electromagnetic spectrum) are not at opposite ends of a uniform linear semantic scale, they are as similar to each other as red is to orange, and violet is to blue (Figure 8).
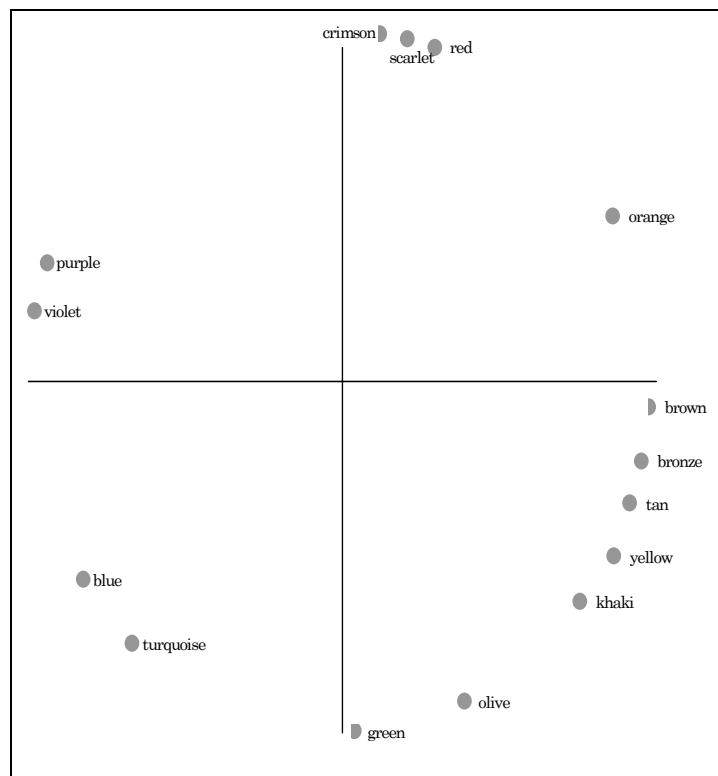
Figure 8.   Multi-Dimensional Scaling Representation of Ekman's (1954) Colour Similarity Data.

One possible solution might be to convey quantitative difference using a limited selection of colours from the colour wheel, for example yellow through green to blue.   Bisantz et al provide an example colour-scale, shown in Figure 9 (Bisantz et al., 2002). The scale in Figure 9 is intended to represent ten levels of probability ranging from 5 to 95% chance of the probability of the presence of mines. This scale seems intuitive viewed as a set. However, there is no guarantee that when viewed individually, the colours will be easily without the aid of a reference chart. Colour hue discrimination, appears to be more suitable to representing category level scaling rather than interval or ratio level scales.
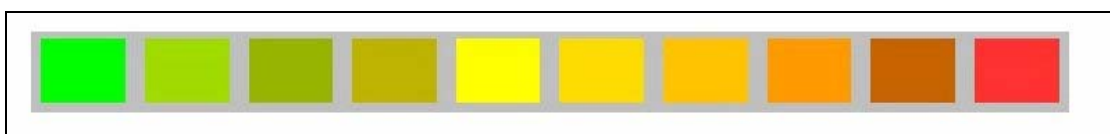
Figure 9: An example colour-scale. From (Bisantz et al., 2002).

2.2.7 Auditory, tactile and olfactory display enhancement

A number of studies have focused upon the use of auditory enhancements for visual displays. A common use of auditory enhancement has been as warning signals (attention grabbing). Early research has indicated that subjects attend to auditory warning signals faster than visual

warnings (Stirner, Siegel, & Baker, 1957), and it has been suggested that auditory warning signals are particularly useful for situations in which the visual system is overburdened (Sorkin, 1987). In addition to general warning signals, stereophonically presented auditory cues have been used as an aid to visual search. For example, a number of researchers have found that aurally presented cues can aid localization in visual search but may not be useful in representing complex information (Flanagan, McAnally, Martin, Meehan, & Oldfield, 1998; Perrott, Cisneros, McKinley, & D'Angelo, 1996), and similar aural cues have been successfully used in applied settings such as fighter-jet cockpits (Sorkin, 1987).

Research indicates that tactile stimulation may be suitable for drawing attention to changes in state such as automated shifting between engine modes. Skylar and Sarter (1999) found that wrist mounted tactile stimulation was able to significantly improve awareness of state changes compared to a visual condition (Skylar & Sartar, 1999). Investigations of the use of tactile enhancement as an aid in localization tasks have been less successful. Gilliland and Schlegel (Gilliland & Schlegel, 1994) investigated the use of head-mounted tactile stimulators that produced a light tapping on the scalp as an aid in detection and localization tasks but found that it interfered with task performance. One possible reason that tactile stimulation was not been found to be useful for localization is that it is difficult to abstract. A sound or a flashing light is interpreted as a signal to orient to the direction of its origin; in other words a sound that appears to be coming from the left is a signal to look left. In contrast to this, somatosensory or tactile information appears to be interpreted as a signal to orient to where the individual is being touched, and because of this, it appears that even with training it may not be a useful enhancement device for localization tasks.

There are few examples of the successful application of olfactory displays and even fewer that can be considered relevant to sub-surface decision making environments. As Sanders and McCormick (1993) indicate, there are a number of potential problems with olfactory displays. First, while the olfactory system is extremely sensitive, it is also prone to false alarm. In other words, subjects tend to report the presence of an odour when no odour has been presented (Richardson & Zucco, 1989). Second, studies have indicated that subjects are able to distinguish between different odours, but have difficulty identifying specific odours when presented in isolation (Desor & Beauchamp, 1974). Third, subjects have difficulty in distinguishing between odours that differ in intensity (Engen, 1982). The last two points highlight the inherent difficulty of encoding multi-dimensional data as olfactory stimuli.

2.2.8 Cognitive Factors: Summary

This section outlined a number of cognitive factors that may influence display utility:

- *Attention limitations and cognitive load.*

- *Short-term memory limitations.*

- *Long-term memory limitations and object representation.*

- *Decision-making heuristics and cognitive load.*

- *The effect of Gestalt grouping principles upon display design*

- *Factors associated with colour-coding such as semantic associations and internal representations of colour similarity.*

- *The relevance and possible uses of auditory, tactile and olfactory display enhancements.*

2.3 Ecological Factors Influencing Display Utility

Here the term *ecological* refers to the real-world setting of display use. All real-world decision-making occurs within a unique system or environment Todd & Gigerenzer (1999), defined by factors such as the type and quality of information that is available, the way this information is organized, the capabilities of the various machines and individuals interacting within the environment, and the types of decisions that need to be made. The decision-making environment can be thought of as an interactive system because the various factors that define the environment impart varying degrees of influence upon each other. For example, if access to information is restricted, then this may influence the ability of the user to make accurate decisions. Alternatively, ample but poorly organized data pose potential problems of their own, such as cognitive overload.

Visual displays currently being used as decision aids in undersea warfare resemble the types of displays conventionally used in aerial and surface warfare. Typically the display provides a representation of a platform's immediate physical surrounds, such as local topography and the location, heading and speed of neighbouring platforms. However, there are a number of factors that differentiate the decision-making environment of sub-surface platforms from other types of platform. For example, unlike aerial and surface platforms, Collins class submarines rely on passive sonar to determine the position, speed, heading and type of local targets. This means that there is often a degree of uncertainty in regards to these factors. Given that the decision-making environment of the Collins class submarines is specific, and differentiated from other types of decision-making environments, it is important that the visual displays employed as decision-making aids be tailored to suit this environment. The following sections outline a number of ecological factors, or factors related to the decision-making environment, that may influence display utility, and some of the associated considerations.

2.3.1 Task requirements

Specific tasks performed by the platform, and the sorts of decisions that are required in regards to performing these tasks, should be a major consideration in regards to display design. To ensure that the displays support the decision-making process, display capabilities should match task requirements as closely as possible. A comprehensive understanding of display requirements can be obtained by assessing the types and frequencies of the various operations such as reconnaissance, aggressive actions, etc that are performed by the platform, and the roles that the commanding officer and support staff play in their execution. A number of different methods exist that would be suitable for obtaining this information, including Task Analysis (Preece, 1994) and Cognitive Workplace Analysis (Vicente, 2002; Vicente & Rasmussen, 1992).

Knowledge of the specific requirements of the display, or displays, to be developed can be used to govern the form and content of the display. For example, if the display is to be used for tasks involving both relative position judgments and shape understanding, then it may be necessary to combine both 2-D and 3-D display formats, or allow the users to shift between the two formats. Additionally, this knowledge can be used to determine what sort of

information needs to be represented explicitly. For example, in a physical display of a platform and its surroundings it may be useful to represent features such as political boundaries and shipping lanes. However, as discussed in the section on cognitive factors that influence display utility, display clutter can lead to a number of negative effects such as cognitive overload. The relative importance and frequency of use of this type of information can be used to determine if this information needs to be explicitly represented in the display, or if it needs to be accessed only when it is specifically needed. Additionally, this can also be used to determine the physical form of the display: 'hidden' functions that are used more than others may need to have 'hot' buttons that provide instant access to the data, whereas space limitations may mean that less useful or less frequently used functions are accessed via a menu.

Research has indicated that the way that data are organized within information hierarchies influences the types of actions that are taken by users. Vicente and Rasmussen argue that interface users can encounter three types of situations: routine, anticipated situations; non-routine but anticipated situations; and non-routine unanticipated situations (Vicente, 2002; Vicente & Rasmussen, 1992). Display interfaces that are only used in routine, anticipated situations only need a limited repertoire of functions, as the range of situations the user faces is likewise limited. In routine and anticipated situations the user only needs access to a limited body of information. However, in unanticipated situations, which often require adaptive problem solving-type behaviour, users may need to have access to a wider range of data and functions

Specific knowledge of display requirements can also be used to determine how data should be organized. The hierarchical structure within which data is organized determines the pathways travelled in order to access information. It is imperative that data be organized in a manner that is plausible in regards to the types of tasks performed. As previously mentioned, it may be useful for display users to be able to superimpose information such as shipping lanes, political borders, weapons range envelopes, and uncertainty ellipses onto the conventional display. There are a number of ways that this information may be organised. One way would be to have a button with an appropriate label such as "Display Enhancements". Pressing this button would provide the user with a menu of the various enhancement types, each of which represented a sub-group of functions or enhancements. However, if certain functions are more important, or are accessed more often than others, than this may not be the most appropriate way of organising the information. Additionally, it may be useful for users to have access to the data being displayed on the other consoles within the operations room. This provides the possibility of information being integrated at lower levels in the chain of information, thereby easing the cognitive load further up the chain.

2.3.2 Information Type

The type and quality of available information will influence display utility. Sub-surface platforms rely heavily upon passive sonar to obtain information about target location, speed, heading and type. This imposes restrictions upon the degree of confidence that can be associated with the data. The representation of data in conventional visual displays is based upon the assumption that the positions of target platforms in relation to ownship are an accurate description of platform locations in the real world. However, given that the type of

information available within sub-surface decision making environments is for the most part uncertain, the representations of these data should reflect the uncertainty. If the locations of target platforms are portrayed as being unproblematic, this may lead to users making decisions based upon inaccurate information. Alternatively, if the degree of confidence in a target's position or type is explicitly represented, it appears sensible though not necessarily the case, that the user take such information into account when making a decision.

A number of possibilities exist for representing uncertainty in a display. For example, location can be represented by a circle or sphere centred on each icon or symbol. The size of the sphere or circle could be determined by representing a Gaussian probability distribution of possible locations. This would provide an indication of the level of uncertainty associated with the target. Larger circles would indicate broader distribution of uncertainty. Likewise, shape, say an elipse, could represent directional variance (skewing of the Gaussian scheme) arising in many sensors. Additionally, using probability distributions to represent uncertainty would allow the user to make assumptions about the location of the target within the sphere or circle of uncertainty, with location probability decreasing as a non-linear function of distance from centre. A number of researchers have tested the usefulness of uncertainty representations such as these. Studies by Andre and Cutler, 1998 (as cited in Bisantz et al., 2002; and Kirschenbaum and Arruda, 1994) both used ellipses or circles to represent uncertainty regarding platform location. Both studies found that subject performance improved significantly when using displays capable of representing uncertainty. St. John, Callan, Proctor and Holste (2000) used irregular ellipses or 'blobs' to convey uncertainty in regards to position and heading. Results indicated that use of the uncertainty representation was able to improve recall of the distance and direction of future enemy positions (St. John, Callan, Proctor, & Holste, 2000a).

A number of alternative approaches have also been suggested. In addition to circular uncertainty representations Andre and Cutler (1998, cited in (Bisantz et al., 2002)) also compared numeric and arc representations of uncertainty in regards to platform heading. The numerical representation involved assigning each platform a numerical value representing heading uncertainty, and the arc representation displayed a curved line that covered the range of possible movement headings (the greater the heading uncertainty, the greater the corresponding arc). The results indicated that each of the three uncertainty representations were able to improve subject performance in comparison to a no-representation condition. St. John, Callan, Proctor and Holste (2000) used simple symbology to indicate three states of uncertainty (high, medium and low) in a tactical decision making exercise. Results indicated that the degree of uncertainty associated with each unit influenced the types of decisions made. No empirical data are available comparing the effectiveness of the displays using uncertainty representations to displays without uncertainty (St. John et al., 2000a).

Bisantz et al (2002) suggested that blurring or degradation could be used to represent uncertainty. The degree of uncertainty could be represented by the degree to which an icon was degraded, with high degradation representing high uncertainty. Although this technique is yet to be empirically tested there are a number of reasons for questioning its utility. In the first place, as has been previously mentioned, blurred or out of focus objects can be distracting and might possibly cause fatigue as the visual system struggles to bring the blurred image into focus. Secondly, the use of blurring or degradation effectively removes useful information from the display: designers should be aiming at *representing* uncertainty within a display, not

creating it. Similarly, some researchers have warned against the use of linguistic representations of uncertainty (such as probable, doubtful, likely), as they are open to individual interpretation, and are therefore unsuitable for representation as a psychological continuum (Bisantz et al., 2002).

There is much that is not yet understood in regard to the manner in which people think about the uncertainty of information and how assisting such thinking through display design might assist decision-making. This would seem to offer a fruitful research direction in the future.

2.3.3 Physical environment

The structure of the physical environment in which the displays are to be used may also impact upon display utility. For example, studies have indicated that stereoscopic and immersed or virtual reality displays are generally more precisely interpreted than screen-based perspective projection displays (Wickens et al., 2000). This research will be addressed in more detail in a later section. Not surprisingly however, the physical limitations of the sub-surface decision making environment may preclude the use of goggle or headset viewed displays. Additionally, audio cues have been used to supplement situation awareness in a number of different applied settings (Sanders & McCormick, 1993). However, a device such as this, that has been found to be useful in the cockpits of single-man fighter jets, may hinder operations in an environment where a number of individuals are working together in close proximity.

2.3.3.1 Ecological Interface Design

One area of research that has evolved from the demand for theoretical tools to govern the design of computer displays is ecological interface design (EID) (Vicente, 2002; Vicente & Rasmussen, 1992). EID has been primarily used in the field of industrial design. Studies comparing EID and conventional interfaces in areas such as pasteurisation, neonatal intensive care, and thermal hydraulic process control micro-worlds have indicated that interfaces designed by employing EID can perform better than interfaces designed by other, more conventional, means (Vicente, 2002). Although it has been suggested that EID should only be applied to work domains that are governed by physical laws and not human intentions (Wong, 1997), there are a limited number of studies in which EID has been applied to command and control situations (Chalmers, Easter, & Potter, 2000; Vicente, 2002).

Chalmers, Easter and Potter (2000) employed EID to develop a threat management display for a Canadian Halifax Class Frigate (Chalmers et al., 2000). The display was intended to provide an overview of the tactical situation using a combination of functional information (such as threat identification, and time until likely weapons release) and physical information (physical location, heading, speed) that was capable of representing air, surface and sub-surface warfare. Rather than attempting to integrate functional information into an already crowded physical display, Chalmers et al (2000) developed two integrated displays (Figure 10). On the right is a conventional 2-D geo-physical display, and on the left a threat overview display. Figure 11 provides a close-up of the threat overview display demonstrating a number of its functions. Target platforms are sorted according to type (air, surface, subsurface or missile),

contact state (unresolved, suspect, hostile, assigned or engaged) and temporal distance from ownship. The threat status of target platforms can be seen to increase as they move closer to the bottom left hand corner of the screen. Chalmers et al (2000) suggest that the display has the potential to increase situation awareness by explicitly representing all target platforms within a hierarchical structure, organized according to task priority. However, as yet, the display has not been tested empirically. The work is presented here to demonstrate the concept of EID.
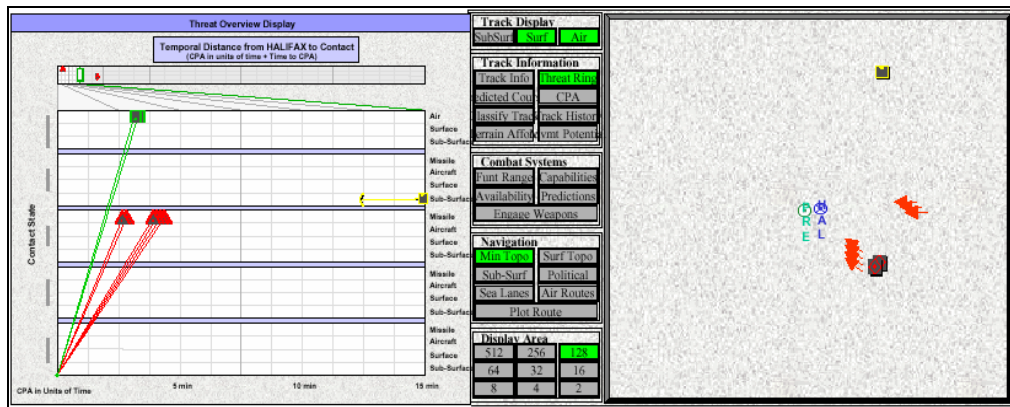
Figure 10.   Integrated display for Halifax Class Frigate. From Chalmers et al (2000).

Bisantz et al (2002) provide a number of examples of displays designed as tactical decision-making aids that were developed using cognitive task analysis (CTA). Like the display developed by Chalmers et al (2000), each of the displays combines geo-physical and functional information and were developed to support the specific needs of the user. Only one of the displays, a visualization of combat readiness for an Army command application (Talcott, Bennet, Martinez, and Stansifer, 2001 cited in Bisantz et al, 2002) had been tested empirically: Bisantz et al (2002) indicate that subjects using the EID display demonstrated superior performance in comparison to subjects using an alternative digital display.
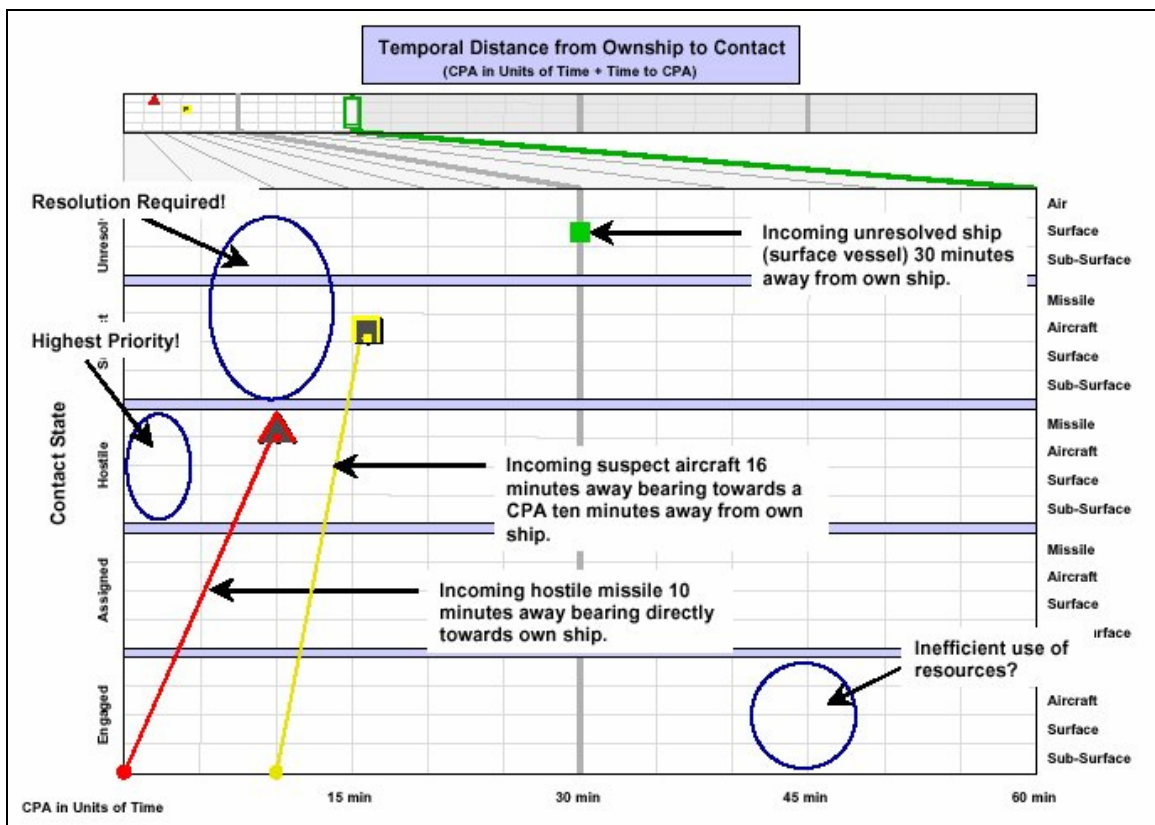
Figure 11. Threat Overview Display. From Chalmers et al (2000).

2.3.4 Ecological Factors: Summary

This section outlined a number of cognitive factors that may influence display utility:

- *The effect of task requirements upon display design.*

- *The effect of information type and quality upon display utility, and the case for representing uncertainty.*

- *Restrictions imposed by the physical environment.*

- *One method of capturing such factors in design is called:*
  Ecological Interface Design.

3. The Comparative Utility of Two-Dimensional Versus Three-Dimensional Displays

Recent technological advances have meant that a variety of 3D display alternatives have become available in addition to conventional 2D displays. Alongside these technological advances has been a growing body of research exploring the practical implications of the new display technology. One area that has received particular interest concerns the comparative utility of 2-D and 3-D displays.

3.1 Display Dimensionality

Various methods have been developed for presenting three-dimensional displays. A number of methods, such as stereoscopic and immersive (or virtual reality) imaging involve the use of goggles or a head-set. Alternatively, three-dimensional perspective imaging can be created on standard computer monitors or view screens. While there is some evidence to suggest that stereoscopic and immersed imaging are superior to view-screen perspective displays in terms of image clarity (Wickens, Thomas, & Young, 2000), a number of studies have reported side-effects such as nausea and dizziness after the use of goggles or head-sets (Regan & Price, 1994). Additionally, in many applied settings the use of view-screens is preferable for practical reasons: for example, many people can potentially view a single monitor, whereas only one person has access to the information presented on an individual head-set. A further argument in favour of perspective displays is that they are computationally less costly. For these reasons the majority of research into 3D display imaging has focused upon perspective displays.

An obvious advantage that 3-D displays have over 2-D displays is the inherent ability to represent explicitly all three spatial dimensions within a single image. Users of 3-D displays have immediate access to information concerning latitude, longitude and altitude, whereas in 2-D displays data relating to one of the three dimensions must be omitted, or encoded either digitally or through analogue markings such as contour lines. Because of this, 2-D displays might possibly impose a greater cognitive load upon the viewer as they shift their attention between the different information types. In light of this, it has been theorised that for integrated attention tasks, or tasks requiring the integration of information concerning all three spatial axes (such as aerial or undersea navigation), 3-D displays should show an advantage over 2-D displays. No such distinction between 2-D and 3-D display formats should be obvious for separable attention tasks in which attention need only be focused upon one dimension (Haskell & Wickens, 1993). Although this distinction seems intuitively plausible, empirical studies have indicated that it provides a poor prediction of comparative display utility. For example, St. John, Cowen, Smallman and Oonk (2001a) summarised 16 recently published studies in which comparisons were made between 2-D and 3-D displays in applied aviation settings. The experimental tasks were classified as requiring either integrated or separable attention, and of the 11 studies classified as integrated, only 4 found a 3-D advantage, whereas 5 found a 2-D advantage and 2 were tied.

St. John et al suggest that the lack of evidence for an integrated task 3-D advantage may be because the distorting effects of 3-D displays outweigh any benefit of integrated viewpoints when making precise relative position judgements (St. John et al., 2001a). 3-D displays are prone to three distortion effects: First, foreshortening or slant underestimation, whereby the relative angles of objects are distorted according to the relative distance between the object and the viewer. For example, a hillside that slopes away from the viewer at 45-degree angle will appear to be more acute the closer it is to the viewer. Secondly, in order to represent three dimensions upon a two-dimensional screen, at least two of the spatial axes must be compressed. As a result of this, parallel lines will appear to converge as they move away from the viewer, and the foreground may be positioned lower on the display screen than the background or horizon. Thirdly, as Figure 12 illustrates 3-D displays are subject to what is termed, "line-of-sight ambiguity". This uncertainty relates to the undefined relationship between size-distance scaling across all three spatial dimensions (that is, the geometry of the image can be identical at any number of different viewpoints of a scene – relative motion appears to help us avoid such uncertainty in natural vision). In a top-down 2-D display, however, all information regarding vertical distances is lost, however distances along the two horizontal planes can be represented without distortion.
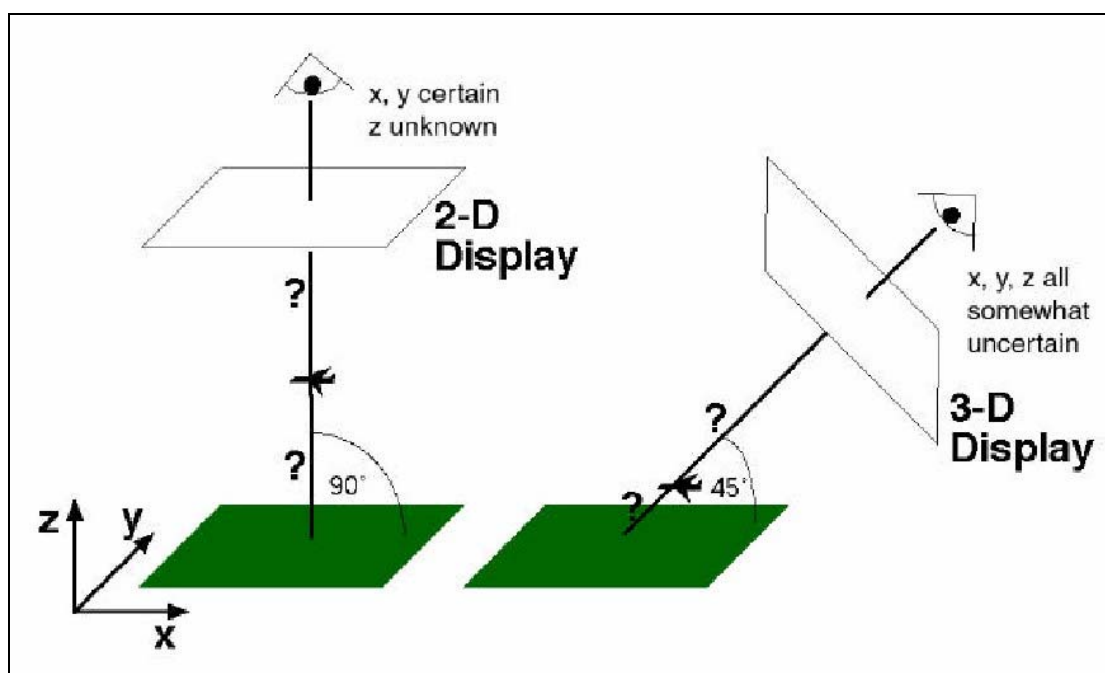
Figure 12. A comparison of line-of-sight ambiguity in 2-D and 3-D displays. From Smallman, St. John and Cowen (2002).

Unlike 3-D displays, 2-D displays are scaled linearly. As a result of this, the relationships between angles and distances within a target environment are preserved within the display. For example, lines that are parallel in the target environment will be parallel within the display. Although 2-D displays cannot provide a comprehensive integrated representation of an environment, the viewer can assume that the representation is accurate. In this way, the relationship between 2-D and 3-D displays can be thought of in terms of a trade-off between information quantity and information quality.

Given the relative strengths and weaknesses of the two display types, St. John and colleagues (St. John & Cowen, 1999a, 1999b; St. John et al., 2001a; St. John, Oonk, & Cowen, 2000b; St. John, Smallman, Bank, & Cowen, 2001b; St. John, Smallman, Oonk, & Cowen, 2000c) proposed an alternative method of determining which tasks might be better served by either display. They argue that 3D displays are most useful for tasks that require shape understanding, such as matching an out-of-cockpit view of terrain with a 2D or 3D digital display, whereas tasks that require precise relative position judgements, such as predicting if two objects will collide on their present courses, benefit from 2D displays.

St. John et al tested their hypotheses by evaluating subject performance upon two abstract visuo-perceptual tasks: object recognition and relative positioning (St. John & Cowen, 1999a, 1999b). In both experiments the subjects were presented with either a 3D perspective view or set of three 2D plan views (top, front and side) of simple 3D block shapes comprised of 10 to 16 cubes (Figure 13). In the first experiment, the subjects were required to identify the target object from a set of spatially rotated alternatives. The subjects were able to perform more accurately and faster when provided with a 3D perspective view. In the second experiment, the subjects were required to indicate the position of a sphere in relation to the block shapes. The 2D display was found to be superior to the 3D display in terms of response times and accuracy.
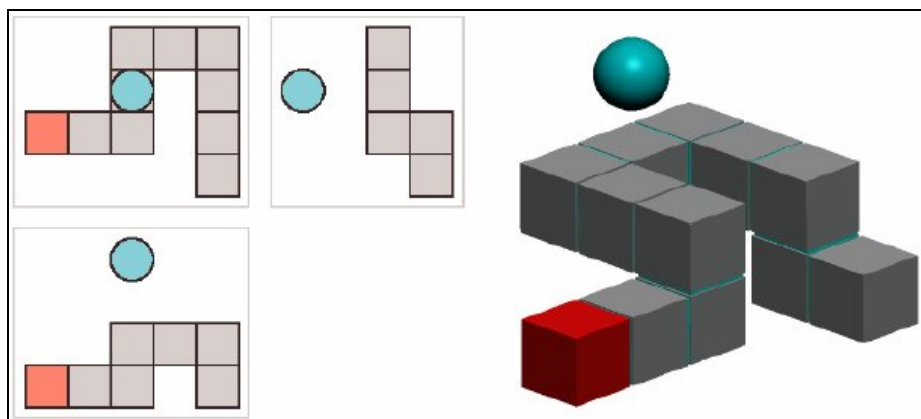
Figure 13. Example of test stimuli from St. John et al (1999). The position of the sphere in relation to the cubes is ambiguous in the 3-D display. However, the 3-D display provides a superior indication of the shape of the block-object.

For the most part, experimental findings across a range of abstract and applied settings have replicated the results of this experiment. We will now review the literature comparing 2-D and 3-D displays in light of St. John and colleagues' distinction between relative position judgements and shape understanding.

3.1.1 Tasks Involving Judgements of Relative Position

Tittle, Woods, Roesler, Howard & Phillips (2001) performed a meta-analysis on eleven separate studies (McKee, Levi & Bowne, 1990; Graham, 1965; Phillips & Todd, 1996; Oomes & Dijkstra, In Press; Fechner, 1860/1966; Lapin & Furqua, 1983; McKee & Welch, 1992; Westheimer, 1975; Tittle, Todd, Perotti & Norman, 1995; Kramher & Fahle, 1996; Norman & Lappin, 1992: all cited in Tittle et al, 2001) in which discrimination accuracy was compared for 2D and 3D versions of seven different abstract visuo-perceptual tasks: judgements of relative distance, relative curvature, global object orientation, distance bi-section, relative size, co-linearity or co-planarity, & flat versus curved categorisation. 2D visualisations were found to be better than 3D across all tasks, with the greatest differences being found for tasks requiring precise quantitative judgements rather than qualitative judgements. Alexander and Wickens cite nine studies involving position estimation tasks in which an advantage was found using 2-D displays (McGreevy & Ellis, 1986; Tharp & Ellis, 1990; Kim, Ellis, Tyler, Hannaford, & Stark, 1987; Barfield & Rosenberg, 1995; Wickens, 1995; Wickens & May, 1994; Yeh & Silverstein, 1992; Boyer, Campbell, May, Merwin, & Wickens, 1995: all cited in (Alexander & Wickens, 2002)). Additionally, St. John et al (2001a) reviewed 14 studies from the aviation literature involving judgments of relative position: seven studies found a 2-D advantage, three found a 3-D advantage and four found no significant difference.

St. John and colleagues performed a series of experiments involving displays of realistic terrain. Subjects were required to perform a number of different visuo-perceptual tasks using three different display conditions: a topographical 2D display, a 45 degree 3D perspective display and a 90 degree topographical 3D perspective display. Performance on a task requiring judgements of relative position, in which the subjects indicated which of two points was higher, was found to be significantly better using the 2D display than the two 3D displays. Additionally, there was no significant difference in reaction time between the three display conditions. This is interesting because it indicates that despite having to search for digital information regarding altitude, the 2D display was still faster than the 45 degree perspective display in which the vertical dimension was explicitly represented (St. John et al., 2000b). Similarly, the 2D topographical display was found to be significantly more accurate and faster than the 3D displays for a task in which subjects estimated the latitude, longitude and altitude distances between two points (St. John et al., 2000c).

In a similar manner Wickens, Thomas and Young (Wickens et al., 2000) compared subject performance on a series of applied visuo-perceptual tasks involving topographic (2D), 45 degree exocentric (CT screen) perspective and immersed (virtual) perspective displays of realistic terrain. Replicating the findings of St. John et al (St. John et al., 2000b; St. John et al., 2000c) judgements of relative distances were found to be significantly more accurate using the 2D display. It is interesting to note that the subjects expressed near-equal confidence in their judgements across the three display conditions, regardless of accuracy. This is particularly worrisome as it indicates that when using the 3D displays the subjects believed they were performing more accurately than they actually were.

3.1.2 Tasks Involving Shape Understanding

Studies of tasks that can be categorised as involving shape understanding can be classified into two groups: view-matching tasks and line-of-sight tasks. The number of studies involving applied shape understanding tasks is much smaller than for relative position tasks and, as such, it is difficult to interpret the findings with any degree of confidence. Despite this, the studies appear to indicate that there may be a time advantage for perspective displays on shape understanding tasks: subjects using perspective displays for shape understanding tasks require less time to produce responses that are equal in accuracy to responses made using 2-D displays.

St. John et al (2000b) compared 2-D topographical, with both a 90 degree (top-down 3-D display) and a 45 degree perspective 3-D display (viewpoint represented by perspective projection at 45 degrees from a central image axis) for a view-matching task in which the subjects were required to match a designated section of a display with one of four immersed perspective views of terrain (Figure 14). No significant difference in accuracy was found between the three displays, although performance using the 3D displays was found to be significantly faster than performance using the 2D display (St. John et al., 2000b). In a similar study by Hickox & Wickens (1999) in which subjects were required to match an out-of-cockpit view with either a 2-D topographical or a perspective display, the results indicated a 3-D advantage. In contrast to these two studies, Green and Wiliams (1992; cited in Lasswell & Wickens, 1995) found that subjects using perspective displays for view-matching were slower and less accurate than subjects using 2-D displays.
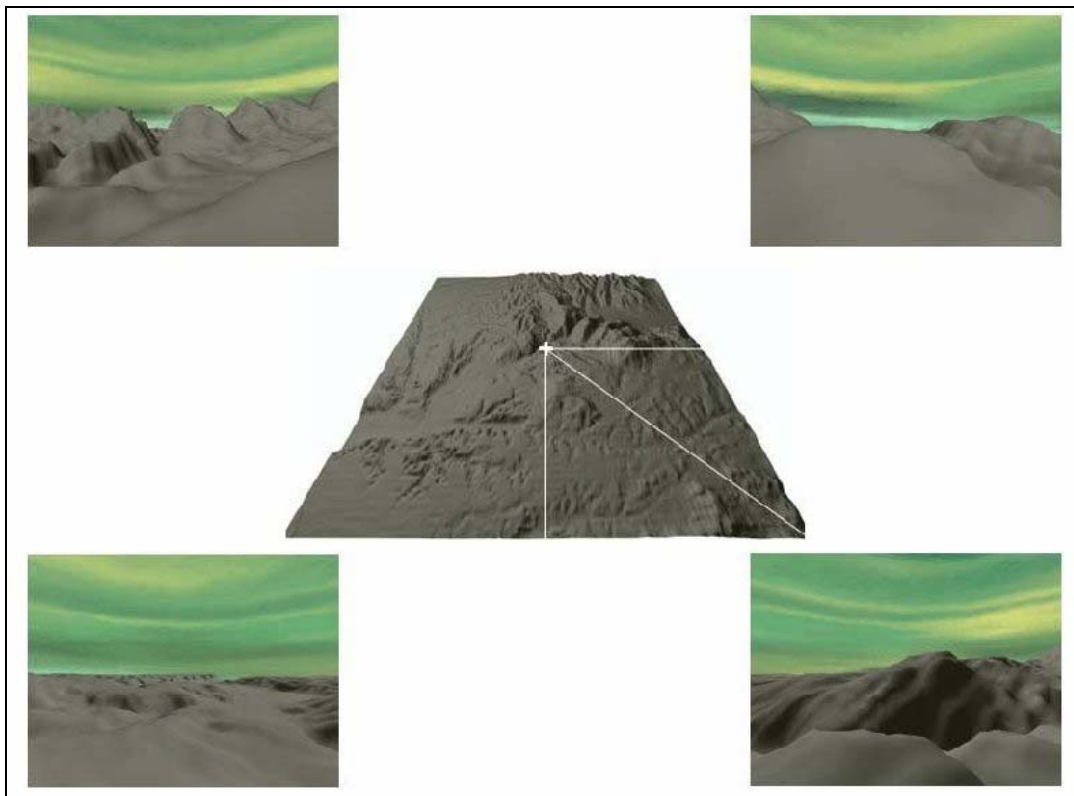

Figure 14.   Example of test stimuli from a view-matching task. From (St. John et al., 2000b)

St. John et al (2000b) found no significant difference in accuracy between 2-D topographical, and 45 and 90 degree perspective displays for a line-of-sight task, in which subjects were required to indicate if a designated point was visible from another point, or if it was occluded by the terrain. Once again, judgments made using the 45 degree perspective display were found to be significantly faster than when using the 2D display, but no significant difference in reaction time was found between the 2D and 90 degree perspective display (St. John et al., 2000b). Additionally, in a task requiring multiple line-of-sight judgments using either a 2D topographical display or a 45 degree perspective display, no significant difference in accuracy was found between the two views, but subjects employing the perspective display were found to be significantly faster (St. John et al., 2001b). In contrast to these findings, a similar study performed by Wickens et al (2000) found no significant difference between 2-D and perspective displays for either accuracy or response time.

Although the literature has provided less than conclusive evidence of a 3-D advantage for shape-understanding tasks, this may in part be due to the type of tasks studied. On the one hand, it appears that relatively few applied tasks actually involve shape understanding. On the other, it could be argued that shape-understanding tasks such as the line-of-sight judgments also involve a degree of relative position judgment (e.g., the relative altitudes of two antennae towers in relation to the altitude of a ridge-line (St. John et al., 2000b)) and this may lessen any advantage provided by the 3-D displays.

3.1.3 Display Augmentation

One approach to improving performance has been to augment perspective displays. Typically the aim of display augmentation has been to remove or reduce the ambiguity associated with perspective displays. For example, a number of researchers have sought to minimize distance ambiguity through the use of drop-lines, shadows or by scaling the size of platforms in relation to distance from viewpoint.

St. John and colleagues found that a 2-D topographical display was significantly more accurate and faster than both a 90 degree top-down 3-D display and a 45 degree 3-D display for a task in which subjects estimated the latitude, longitude and altitude distances between two points (St. John et al., 2000c). However, when grid and contour lines were added to the displays, performance on the 90 degree 3-D display improved to the level of the 2-D display. Performance on the 45 degree display did not reach the same level as performance on the 2-D display, but the proportion of correct responses did more than double.

Smallman, Schiller and Cowen (2000) performed a study of display augmentation techniques in which subjects were required to reconstruct the relative positions of objects within either 2-D or 3-D displays. Platforms in the 3-D displays were either un-augmented, or were augmented with either drop-lines, drop-shadows or size-scaling (maintaining relative size-distance proportions). Performance using the 2-D display was found to be significantly superior to the un-augmented 3-D display. Size-scaling did not improve localization accuracy, but the addition of either drop-lines or drop-shadows improved subject performance to the point that there was no significant difference between performance using the drop-line or

drop shadow augmented displays and performance using the 2-D display (Smallman et al., 2000).

Although relatively few studies have focused upon display augmentation the early indication is that performance on relative position tasks using 3-D displays can be improved to equal or near equal the level of performance using 2-D displays. However, two points should also be considered. First, these findings are as-yet un-replicated. Secondly, Smallman et al warn that the potential benefits of augmentation may be offset by a rise in cognitive effort due to excess display clutter (Smallman et al., 2000).

3.1.4 "Orient and Operate"

As previously mentioned, many of the applied tasks for which visual displays are used appear to involve elements of both shape understanding and relative position judgments. Given that 2-D displays appear to be better suited to relative position tasks, and 3-D displays better suited to shape understanding tasks, this presents a dilemma in terms of choosing the most suitable display format for the task. St. John and colleagues (St. John et al., 2001b) have suggested that one possible solution is to adopt a strategy that they call "orient and operate" in which users can switch between display types. In this way a perspective view can be used to obtain orientation within the target environment, and a 2-D view can be used to perform operations involving precise quantitative judgments. The "orient and operate" format was tested in an experiment in which subjects positioned a series of antennae towers within a realistic terrain environment, such that the towers were within line-of-sight of each other but hidden from enemy emplacements. Each problem had to be solved within a four minute time-period. Subjects were presented with one of three display conditions: a topographical 2-D display, a 45 degree perspective display or a side-by-side display in which both 2-D and perspective views were simultaneously shown. The results indicated that the side-by-side condition led to the fastest solution times and the fewest number of incomplete problems.

There are a number of unresolved problems associated with changing between 2-D and perspective view formats, such as maintaining associations between display elements as the view changes, and how platforms should be represented in 2-D and 3-D displays. Despite this, the idea of designing displays that are capable of providing interchangeable 2- and 3-D views seems promising. Submarines operating in littoral environments typically perform both relative position and shape understanding tasks. For example, it is necessary to constantly monitor the positions of entities within the waterspace, and this can be seen as a relative position task. Additionally, display users are also required to perform shape understanding tasks such as determining constraining parameters like undersea topography, bathymetry and possible courses of action that may pose a threat. Rather than compromise the display users' ability to perform either of these types of tasks, it may be better to provide an interchangeable display.

3.1.5 Relative Utility of 2-D and 3-D Displays: Summary

This section summarised research findings pertaining to the influence of display dimensionality upon display utility:

- *A number of theoretical concepts relating to display dimensionality were outlined, such as integrated versus separable attention, and relative position versus shape understanding tasks.*

- *Research has indicated that 2-D displays may be better for tasks involving judgements of relative position, and 3-D displays may be better for tasks involving shape understanding.*

- *It may be possible to lift performance on relative position tasks on 3-D displays through the use of display augmentation.*

- *An alternative solution is to allow users to change between 2-and 3-D views according to specific task requirements.*

4. Relevance of the Generative Transformational Approach to Visual Perception

Theories of visual perception seek to account for the processing of the non-symbolic aspect of images. In contrast, many questions concerning display design have to do with the combination of symbolic data and information that is more directly representational. Even in the case of the latter type of information, the representation may be of a conventional kind (e.g., the use of a battleship icon), rather than one dictated by purely optical constraints, as in natural perceptual situations. Because the relations between the processing of visual information and that of symbolic representations concerns two highly complex areas, there is no well-developed theory encompassing both. As a result, there is no over-arching body of theory that is immediately applicable to the design of visual information displays. However, theoretical accounts of visual perception have been developed that have some bearing on the design and layout of both symbolic and representational visual displays.

So far as the perceptual aspect of displays is concerned, it is convenient to distinguish three main approaches. These focus on successive stages of the processing of visual information by considering (1) the geometry of projected images, (2) the responses by specific cells and channels, and (3) the contribution by cognitive processes. Recently, Vickers (2001; 2002) has developed a *generative transformational* (GT) theory that attempts to bring together these different approaches. The generative transformational theory of visual perception and the general properties of the generative transformational approach are outlined in Appendix 1. This section outlines the relevance of generative transformational theory to display design and suggests a number of possible research directions.

4.1 A generative transformational approach to human information processing.

The GT approach is implemented in a computational model that gives a quite comprehensive account of the visual perception of structure, motion and depth. The model is productive and yields quantitative predictions for a wide variety of situations. In principle, the GT approach is potentially relevant to a wide range of purely perceptual questions concerning display design. The following is a tentative classification of the general kinds of questions for which the GT approach might have some application:

1. *Questions concerning the display of information concerning relative position (e.g., whether 2D or 3D displays are more effective).*
   Because the GT approach is specifically concerned with information about relative position, this involves a fairly straightforward application of the theory.

2. *Questions concerning the recognition of shapes at different orientations.*
   Because the GT approach is concerned with finding the simplest transformation that will map one part of an image onto another, or on to another image, such questions also involve quite natural applications of the theory.

3. *Questions concerning optimal display layout.*
As noted earlier, it is frequently recommended that designers of display layouts should be aware of Gestalt principles, such as proximity, continuity and regularity when positioning display information (Helander, 1987; Wickens & Carswell, 1995). A possible advantage of the GT approach is that it provides an integrated and quantitative underpinning for the above Gestalt principles. In particular, the GT approach can provide an explanatory framework in which to consider effects of the following factors:

    a. Rescaling
    b. Element density
    c. Clustering, regularity and symmetry
    d. Continuity, closure and colinearity
    e. Boundary shape
    f. Order of scanning

4. *Questions concerning the relationships between perception and action.*
Because, the GT approach considers perceived organisation as corresponding to something like an implicit plan for action, this approach may have some relevance to problems concerning the compatibility, or otherwise, between display presentation and possible action.

5. *Questions concerning the integration of internal structure and overall shape and orientation.*

The GT approach uses a variety of statistics on information about relative position to select transformations that provide an economical specification of internally structured shapes at particular orientations. Although this aspect of the GT theory is still undeveloped, the general direction that such development might take would probably involve some compromise between economy and accuracy in specifying internal structure.

4.2 Two illustrations of the possible relevance of the generative transformational approach to display design.

The GT approach has been developed to account for the results of laboratory studies relevant to theories of visual perception, rather than to address the problems of display design. The theory has also been primarily addressed, in the first instance, to the results of experiments employing spatial point patterns. However, there is no reason, in principle, why the theory can not be extended to deal with bit map images, for example. Similarly, the theory can be generalised to deal with any set of elements, with multiple sets of elements and with elements that have unequal weights.

Meanwhile, there are two principal aspects of the theory that seem most relevant to the problems of display design. The first concerns the dependence of the theory on information about the relative positions of image elements. The second concerns the selection of transformations that maximise self-similarity within a representation or between two spatially or temporally distinct representations.

First, in sections 3.1 and 3.2, evidence was reviewed that indicates that performance on tasks requiring judgements of relative position tends to be better with 2D than with 3D displays. This is qualitatively in line with what might be expected on a GT approach for the following reasons.

Interactions between events tend to occur between neighbouring events. Accordingly, the GT approach makes use of a set of techniques, termed *nearest neighbour analysis* (NNA). These techniques differentiate between rival hypotheses about the processes that underlie the spatial distribution of these events. NNA achieves this differentiation by characterising the distribution of distances between similar events that are nearest (second-nearest, ..., k-nearest) neighbours and contrasting this with the distribution that would be expected if the events in question were distributed in a completely random manner.

NNA provides a powerful analytic framework for the detection of structure, motion and depth in arrays of elements, random or otherwise. For example, in machine vision, Zahn (1971) has presented an analysis of the detection of clusters in terms of nearest neighbours (NNs). NN relations are consistent with the view, proposed by some cognitive theorists, that perception organises stimuli in an optimum way (e.g., producing the shortest path). NN structures are independent of the order in which the elements are considered or an array is scanned. NN structures have considerable redundancy, and so are insensitive to moderate amounts of noise. Evaluations of applications of NNA to automatic image classification in a military context have concluded that it provides an efficient tool for scene analysis, with performance that, like that of human beings, shows only a graceful degradation as more noise is added to a pattern (Singh, Haddon, & Markou, 1999).

Although no investigation has yet been undertaken of the effect of perspective transformations on the distribution of NNs, preliminary explorations with shears suggest that this distribution is relatively insensitive (but not invariant) to shears applied to planar arrays. This goes some way towards explaining the apparent superiority of 2D displays of information about relative position. Because NN distributions remain invariant under similarity transformations, 2D displays, in which variations are restricted to similarity transformations, would be expected to produce more accurate performance than 3D displays that incorporate perspective transformations, and hence some distortion of the NN distributions - particularly if the rotation of a three-dimensional shape results in the occlusion of different parts of that shape.

A second general finding from comparisons of 2D and 3D displays, discussed in section 2.3, is that subjects required less time to recognise transformed shapes when these were presented in a 3D perspective view than when the shape information was presented as a set of three 2D plan views.

This finding is broadly consistent with a GT approach to visual perception. For example, if an outline shape is transformed in such a way as to be consistent with the projection of a rotation in depth of that shape, then there are certain relations between array elements that remain invariant and can be used to select and guide the transformation required to match the original with the transformed shape.

Specifically, if lines joining contour points to the centroid of the two-dimensional projection of an outline shape are continued, so that they intersect the contour on the opposite side, then the ratio between the first to the second distance remains the same under rigid transformations of the shape. As this diameter is incrementally rotated, successive values of the ratio provide a waveform that is characteristic for that shape, irrespective of its orientation in three dimensions. This invariance can be used to guide the search for a transformation that will match the transformed shape with the original. A similar technique has been used by Vickers, Lee and Chandrasena (2002) for the automatic recognition of logos that have been degraded by noise and subject to various transformations.

The case when the image is a planar array of elements has not yet been systematically investigated. However, preliminary explorations suggest that the distribution of NN distances (which captures the internal structure of the array) also remains relatively unchanged, despite radical shearing. This means that the search for a transformation to relate a given array to a transformed version can also be constrained (though perhaps less tightly) by certain regularities.

According to the GT approach, the visual system uses such constraints to guide the search for a transformation that maps one part of a representation on to another or that maps one representation on to a spatially or temporally distinct representation. Successful mapping corresponds to the recognition of a presented shape as being essentially identical in outline and/or or internal structure to a projected view of that shape at a different orientation.

When information about a three-dimensional shape is conveyed by the simultaneous 2D presentation of three orthogonal plans, the subject (presumably) has to mentally rotate the transformed shape so that one or more projections coincide with the presented plan(s). Alternatively, the subject must somehow integrate the plans into a 3D representation that can be rotated to match with one of the presented possibilities. If we make the reasonable assumption that information about inter-element distances is processed in parallel, but that the rotation and integration processes are serial and effortful cognitive activities, as suggested by the results of a number of studies (Shepard & Cooper, 1982), then this additional processing load would explain the finding that shape recognition is more efficient with 3D displays.

4.2.1 Future Research Directions for the Generative Transformational Approach

Corresponding to the two main applications identified above, there are two main ways in which the supporting perceptual theory might be developed to provide more effective and precise guidance for display design.

The first concerns the detection and characterisation of structure in a display or element array. Nearest neighbour distributions - and cumulative distributions and radial-based functions based on them - are sensitive to the presence of many types of structure. However, it is possible that an even more general approach, which would include nearest neighbours as a

special case, could be developed, based on the use of Voronoi diagrams and Delaunay triangulation (O'Rourke, 1994). For example, recent research has shown that human beings are capable of finding near-optimal solutions to visually presented optimisation problems that are computationally difficult or intractable (Graham, Joshi, & Pizlo, 2000; Vickers, Butavicius, Lee, & Medvedev, 2001). Delaunay triangulation can be used to narrow the search for such minimum structures (e.g., minimum spanning trees and solutions to Euclidean travelling salesman problems), and the cumulative distributions of the areas of Delaunay triangles appear to differentiate between structure and randomness – and between different types of structure – in a very efficient manner.

To our knowledge, such an approach has not been considered in psychological or neurophysiological studies of visual perception, and the development of a set of statistical techniques – and a corresponding perceptual model – based on Voronoi diagrams and Delaunay triangulation would constitute a major research effort. However, we have already established the general direction that such an investigation might follow through our development of techniques of nearest neighbour analysis. There are also strong indications from the literature on computational geometry that such a research initiative would be extremely productive (e.g., Asano, Bhattacharya, Keil, & Yao, 1988; Jaromczyk & Toussaint, 1992).

The second direction for further research concerns the integration of information about outline and internal structure in the perception of shape and orientation in depth. Because no systematic account of internal structure has been developed, little research has been carried out on this question. It is known that highly regular structures (unsurprisingly) produce more accurate judgments of slant. It is also known that judgments of slant are influenced by element density. However, no theoretically motivated, quantitative analysis has been carried out on the relation between such judgments and element density or regularity. The techniques of nearest neighbour analysis provide a potentially useful tool for investigating such questions.

4.2.2 Generative Transformational Approach: Summary

In this section the relevance of the generative transformational theory of visual perception to display design was outlined:

- *Some of the general kinds of questions for which the GT approach might have some application were summarized, including questions concerning the display of information concerning relative position, questions concerning the recognition of shapes at different orientations, questions concerning optimal display layout, questions concerning the relationships between perception and action, and questions concerning the integration of internal structure and overall shape and orientation.*

- *Two principal aspects of the theory that seem most relevant to the problems of display design were illustrated.*

- *Potential future research directions were outlined.*

5. Assessing Display Utility

5.1 Subjective and empirical data

Two main approaches have been taken to assess display utility: subjective ratings and empirical testing. In the following section some of the advantages and disadvantages of these two approaches will be outlined briefly.

Subjective ratings are introspective, in that they are reliant upon test subjects' personal accounts and opinions. Such ratings are generally obtained through simple questionnaires or interviews, and can be sampled either during or after testing. While subjective ratings can be useful, there are restrictions upon the types of data that they can supply and the confidence with which the data can be interpreted. In the first place, introspective judgments of performance (such as asking subjects which experimental condition they believed that they performed the best in) should not be used as a replacement for empirical measures of task performance, as perceptions of global task performance are likely to be subject to memory limitations. For example, overall performance may be high, but if mistakes are more frequent in the last half of the test the subject may perceive global performance as being poor. Additionally, if subjects do not receive feedback as individual tasks are completed, rating of performance might reflect task difficulty rather than success rate.

Secondly, data about subject preference (for example, "do you prefer display A or display B?") should be interpreted with caution, for as Andre and Wickens (1995 cited in St. John et al., 2000b) note, people do not always want what is good for them. For example, in an experiment comparing the performance of subjects on a visual identification task using either 2-D or 3-D displays Baumann, Blanksteen and Dennehy (1997) found that subjects indicated a preference for the 3-D displays, even if their performance was significantly better using the 2-D display (Baumann, Blanksteen, & Dennehy, 1997). Using subject preference ratings to determine display design should probably be avoided, as it is difficult to determine if the users are stating a preference in terms of aesthetics, utility, or some other criterion.

Thirdly, the use of subjective ratings raises the issue of reliability. Because subjective ratings are indications of individual opinion, there is no way of ensuring that the participants are applying the same standards to the problem. One subject's opinion of what constitutes a good performance might be completely different to another subject's. Different subjects might be applying different criteria, such as perceived difficulty or perceived percentage of trials correct, to assess performance. Additionally, there may be variation between subjects in terms of how they weight their assessments: "good" for one subject may be "excellent" or "average" for another. Finally, subjective rating is open to assessment variation both within and across trials.

Bearing these problems in mind, it is important to note that subjective rating can provide valid and replicable data, provided that they are used in the right situations. One type of subjective measure that has proved to be of interest in a number of areas is subject self-rating of confidence, and this will be explained in more detail below.

Empirical data are obtained from the observation of subject behaviour under experimental conditions. The advantage of empirical testing is that it is more objective and can often be gathered unobtrusively. Consequently, empirical data can be considered to be a more accurate indication of performance than data that are gathered using subjective measures. Additionally, empirical tests are able to assess performance in terms of fixed criteria that can be applied across all test subjects and experimental conditions, thereby allowing meaningful comparisons to be made between both groups and individuals, across trials and across time.

5.2 Performance measures

A number of different performance measures are available for assessing display utility. Perhaps the most obvious measure of performance is percentage of correct responses, usually referred to as accuracy. Accuracy scores can be obtained for individual sub-tests, which can in turn be combined to provide a measure of global performance. Endsley (1995a) cautions against the use of global measures when assessing situation awareness, as an overall performance score cannot provide information about the various areas of strength or weakness. For example, performance may be high in all areas but one, resulting in an overall high score but providing no indication of the area of weakness.

Chronometric measures such as response time and completion speed have been widely used in conjunction with accuracy scores as a means of assessing display utility. It is generally recommended that researchers collect both chronometric and accuracy data, as this provides a more complete view of task performance than either measure alone. For example, performance may be more accurate in one experimental condition, but the subjects may take longer to complete the task. This information could be of vital importance when one considers that in practical situations display operators are often required to make accurate decisions in limited time. The advantage provided by a particular display configuration may not be worth the amount of time needed to make the decision.

In some studies response time has been used as the sole measure of task performance. This can be useful in situations for which an accuracy measure is inappropriate. For example, in a study by Bauman et al (1997) subjects were required to identify descending aircraft using either a 2-D or 3-D display (Baumann et al., 1997). Of prime importance in this instance was how long the subjects took to access the data, not how accurate they were because information regarding platform heading was explicitly represented in both displays, so subject accuracy was expected to be high. Another example is a study by St. John and colleagues in which subjects were required to create a chain of antennae towers that were within line-of-sight of each other but hidden from enemy towers (St. John et al., 2001b). During the course of the task the subjects were advised as to whether the placement of each tower contravened task requirements. As a consequence of this, no meaningful accuracy score could be collected, but the display conditions could be differentiated in terms of speed of task completion.

Subjective confidence judgments are a less common form of performance assessment than either accuracy or response time measures. However, they can provide important insight into subject responses. For example, the results of a study by Wickens et al (2000) indicated that

subjects responded with equal confidence regardless of experimental condition, despite the fact that there were significant differences in accuracy between each condition (Wickens et al., 2000). Confidence is usually measured by asking subjects to indicate how confident they were of a response by marking a point on a scale, ranging from low or no confidence to high confidence. To ensure that the subjects give equal consideration to the full range of choices, the number of items on the scale should probably not exceed the limits of STM capacity (7 +/- 2 items), and any fewer than 5 items will not provide the subjects with a large enough range of choices. Additionally, designers should avoid using an even number of items, as they do not allow the subjects to mark a mid-point.

On the other hand Vickers, (1979) and Vickers & Lee (1998) suggest that there is well-replicated evidence that accuracy, response time and confidence levels fluctuate in meaningful and predictable ways. Generally speaking, when subjects are required to respond as accurately as possible (as opposed to responding as quickly as possible), accuracy and confidence tend to be positively correlated, and accuracy and response time, and response time and confidence tend to be negatively correlated. Additionally, response times tend to be longer and confidence scores lower for incorrect responses in comparison to correct responses. Knowledge of this performance measure interaction can be useful when interpreting data, particularly in regards to response bias and response utility. For example, in a 2 choice situation, if the likelihood of making a correct decision is greater for one response than the other, subjects will make that choice more often and their corresponding confidence responses will be high. Alternatively, if the benefit of making one response is greater than the other, subjects will be biased toward making that response regardless of the likelihood of that response occurring. Response times and accuracy scores may be the same as in the previous instance, but confidence scores can be expected to be lower.

5.3 Assessing Display Utility: Summary

This section outlined a number of factors relevant to the assessment of display utility:

- *Subjective and Empirical data were described and their comparative appropriateness was evaluated*

- Various performance measures and their uses were described

6. Future Directions for Research in Submarine Display Design

While reviewing the literature on visual display design it became evident that there was a need for research to be conducted in three specific areas. The following section outlines these recommended future directions, and provides preliminary recommendations of how research in these areas might proceed. Research in these areas has the potential uncover important novel theoretical developments and new technologies.

6.1 Visualising Uncertainty

As has been mentioned, there is a pressing need to develop ways of visualising uncertainty. While this has been recognised in the literature (St. John et al., 2000a), there are, as yet, few empirical investigations of the problem. The fundamental question is, of course, how uncertainty should be visualised formally. A number of different methods have been proposed, including numerical representations, ellipses, colour coding, and blurring. However, there have been no investigations of what types of visualisation methods are suitable for particular situations. Additionally, it may be that particular visualisation methods are only suitable for representing specific types of uncertainty. For example, ellipses may be best suited to representing positional uncertainty, but not type uncertainty.

The problem is further complicated when considering that multiple uncertainties may need to be represented simultaneously. For example, in sub-surface environments it is not uncommon for there to be a degree of uncertainty associated with the type, position, heading and velocity of a target platform. Simultaneously representing multiple types of uncertainty poses a number of problems. First, given that there may be a restricted number of plausible ways of representing uncertainty, there may be restrictions upon the number of dimensions that can be represented concurrently. Furthermore, there has been no research into how different combinations of simultaneously represented uncertainty visualisations might interact.

An additional problem that needs to be addressed is how particular distributions of uncertainty should be represented. For example, positional uncertainty is often represented by an ellipse. If the uncertainty data are drawn from Gaussian distributions then the centre of the ellipse represents the point of greatest certainty in the position of the target platform, with certainty decreasing monotonically towards the edge of the ellipse. However, if the distribution is actually bi- or multi-modal, then such a representation poses problems. Representing bi-modal distributions with ellipsoid may create the impression that the point of greatest certainty is central when this is not the case.

Ideally, what is required is the capability to display uncertainty about both physical and abstract variables simultaneously, in a way that is accurately and effortlessly comprehended by the display user. For example, consider a scenario where sensor data implies a multi-modal probability distribution for the location of a sub-surface object, and gives a set of classificatory

probabilities for what the object is. Developing psychologically principled techniques for representing this uncertain information is an important and challenging problem. Its solution would significantly enhance the utility of data visualisation systems in the submarine environment.

An obvious method of testing the comparative utility of rival uncertainty representations would be to measure the performance of subjects on real-world tasks using the various uncertainty representations. Subjects could be randomly assigned to either a control group or a treatment group. Both groups would perform the same task, for example they may be required to locate target platforms and identify the platform's type, speed and heading. In the control treatment uncertainty could be represented by numerical data, whereas in the experimental treatment uncertainty might be explicitly represented. In addition to task performance, it might be appropriate to measure response time and accuracy. Comparisons could then be made between the two conditions.

6.2 Decision Support Systems

Real world human decision making involves large amounts of incomplete, uncertain and unreliable information, and is set in a complex and richly structured environment that is changing constantly. Set against these challenges, it is not surprising that most of the real world decisions made by people resist complete formal characterisation, and so are difficult, if not impossible, to automate fully in artificial systems. Nevertheless, it is useful, where possible, to automate some of the more routine parts of human decision making that are well understood. This reduces the cognitive load on users, and allows their limited decision making resources to be focussed on the most difficult problems. The remarkable abilities of human visual and cognitive processing are best used to detect patterns, draw inferences, make generalisations, develop and test hypotheses, generate queries, and work towards conclusions that are not easily automated.

Decision support systems attempt to achieve this balance by using decision making models for simple tasks, or to suggest possible answers, requiring human confirmation, for more difficult tasks. In this way, decision support systems become tools that extend human decision making capabilities, providing not only an interface to the information needed for better decisions, but also bearing some of the decision making load.

A considerable body of applied and theoretical research in psychology, cognitive science, computer science, and other fields has been devoted to developing and evaluating decision support systems. A number of automated decision aids are currently being developed for military applications (Liebhaber & Feher, 2002). The most significant challenge, and the area with the greatest potential for a "game changing" advance, is in developing suitable cognitive models of human decision making. One possible research direction is to use the ecologically rational or 'Fast and Frugal' decision making heuristics outlined by Todd & Gigerenzer (1999). There is considerable empirical evidence to suggest that human decision making closely resembles Gigerenzer's ecologically rational model, and unlike alternative non-classically rational models such as Klein's (Klein, 1999) 'Naturalistic' decision making model, 'Fast and Frugal' heuristics are easily operationalised as decision making algorithms. Although no

single algorithm may be able to deliver an optimal solution to a problem, an algorithm based upon a model of human decision making may be able to produce human-like responses, thereby considerably lessening the cognitive load of the users.

One way of testing the effectiveness of decision-making heuristics would be to compare the performance of various decision-making models with the performance of human subjects. In order to do this it would be necessary to gather information about the various cues that experienced individuals use to perform real-world tasks. For example, it should be possible to gather a list of all of the cues used in Target Motion Analysis. Expert users would then rate these cues in terms of their effectiveness or salience. A number of rival models could be developed, for example, 'Fast and Frugal models' using minimal cues, and 'Unbounded' or traditionally rational models (such as multiple regression) using all of the cues.

Of course the human capacity for decision making need not necessarily bound the decision support technology or processes. The most effective decision making model is that model that makes the best the most effective decisions whether framed by human performance or purely machine generated or some combination of both.

6.3 Exploiting the Human Facility to Interpret Affective Data

Affect is a general term that is used to encompass a range of phenomena related to emotion and mood. It is also used to refer to ideas such as feelings, mental state, unease and trust. The expression and recognition of affect is crucial for the communication of understanding. If expressive components of affect play an essential role in the communication of internal states and the promotion of natural interactions, endowing our computer systems with expressive skills may enable us to capitalise on the inherent human facilities that support social interaction.

Because affective information is readily interpreted, the potential exists for using affective information to convey uncertainty data. For example, a decision support system may be able to provide an interface user with a number of potential action plans. Each of these plans may have an associated degree of uncertainty. Avatars (i.e., human like computer representations) could be used to convey the various plans, thereby simultaneously imparting affective information to the interface user that can be interpreted in terms of uncertainty. In other words, avatars of an untrustworthy appearance might convey high-risk plans, and honest or reliable looking avatars could convey information that has a high degree of associated confidence.

More generally, there is an enormous untapped potential for using affective information, like emotions, to improve data visualisation systems. Human decision making evolved in an environment where both affective information and abstract conceptual information were important. This suggests that information might be communicated to people in both ways, conveying some data, like trustworthiness of reliability, that are well suited to affective representation through emotions, and conveying other data, like spatial position, that are more abstract and conceptual in nature through conventional means. The potential benefit of adopting this approach is two-fold. First, it is likely a greater volume of data could be

conveyed more rapidly, because a greater array of the possibilities for communicating information to people is being used. Metaphorically, using a new protocol has increased the bandwith of the communication channel between the data and the human. Secondly, some aspects of the data, like reliability measures, are better communicated in an affective form. Human decision making will be enhanced because the users can 'feel' that some information is unreliable, rather than have to integrate this knowledge as a separate abstract conceptual fact. Metaphorically, the new affective protocol provides a better encoding of some aspects of the data, and so allows these data to be accurately and effortlessly understood.

Testing the usefulness of affective data as a decision support aid could be achieved using a similar methodology as could be used for testing uncertainty representations (see above). Subjects could be randomly assigned to either a treatment or control condition, and their performance on a simulated real-world task could be measured. Subjects in the control condition might be asked to perform a task with conventional, non-affective decision support, whereas subjects in the experimental condition would be provided with decision-making support with an affective component, perhaps in the form of an avatar that would offer advice on key decisions. The uncertainty associated with the avatar's advice could be represented by manipulating the facial features or voice of the avatar. In other words, uncertain information would be conveyed by avatars with an untrustworthy appearance, and certain information conveyed by trustworthy-looking avatars. If affective decision support is a useful device then the performance of subjects in the experimental condition should be better than the performance of subjects in the control condition.

6.4 Research Directions: Summary

This section outlined three areas that have been recommended as areas for future research:

- *Visualising uncertainty*

- *Decision support system*

- *Affective data*

- *Examples were provided detailing how these areas might be empirically researched.*

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Appendix A: The Generative Transformational Approach to Visual Perception.

A.1.   Theories of visual perception

So far as the perceptual aspect of displays is concerned, it is convenient to distinguish three main approaches. These focus on successive stages of the processing of visual information by considering (1) the geometry of projected images, (2) the responses by specific cells and channels, and (3) the contribution by cognitive processes.

*Geometrica*l approaches to both human and machine vision (e.g., Van Gool et al., 1994; Mundy & Zisserman, 1992) generally focus on analysing invariant properties of a projected image that result from various interactions between a light source, an object or scene and an observer, and provide information for the perception of depth and three-dimensional layout in ecologically representative situations. These properties include invariants associated with the perception of shape, slant, biological motion, the direction of self-movement and imminent collision (e.g., Wagemans et al., 2000; Cutting & Readinger, 2002).

Neurophysiological theorists concentrate on explicating the relations between the visual image and the response of specific cells and on trying to reconstruct an organised 'perception' from their interactions (Bullier, 2002). A related, but somewhat different, approach has been pursued by researchers who believe that complex perceptions can be assembled from the responses of filter mechanisms that are sensitive to extended visual patterns, characterised by different spatial frequencies (Westheimer, 2001).

Cognitive theories emphasise the contribution of 'higher-level' brain processes that, it is claimed, are necessary to interpret the underdetermined responses by the visual system to the information presented by an ambiguous image. Cognitive theorists look for explanations of perceptual achievements in terms of general optimising principles, such as maximising symmetry, simplicity or likelihood. (e.g., Dodwell, 1992; Chater & Vitányi, 2003; Feldman, 2000).

A.2.   A generative transformational theory

Recently, Vickers (2001; 2002) has developed a *generative transformational* (GT) theory that attempts to bring together these different approaches. According to this approach, the visual system uses information about the relations between the positions of elements composing an image to select geometrical transformations that, when applied to these elements, generate a representation that maximises the degree of self-similarity within the representation and minimises the difference between the representation and the current retinal input. In other words, the visual system is thought to construct the most parsimonious description of the image elements, consistent with the original image. (Here, the term 'self-similarity' is used in a

generalised sense to mean a statistical resemblance of any one part of the representation to any other part, including the whole representation.)

The idea motivating this approach is that of fractal compression, in which the information in an image is encoded in the parameters of a collage of transformations that, when applied recursively to a small set of image elements, are capable of generating a close statistical approximation to the original image (Barnsley & Hurd, 1993). However, the process by which this compression is achieved in the GT approach is biologically inspired, rather than based on computational techniques developed in the field of machine vision. In particular, the selection of appropriate transformations is assumed to be guided by relational information about the positions of stimulus elements. The pivotal assumption here is that processing by the visual system depends on relations between nearest (nearest, second-nearest, …, k-nearest) neighbours, rather than on absolute distances.

A second important aspect of this approach concerns the interpretation of the hypothesised transformations. An underlying assumption is that these transformations have evolved from the internal direction of overt actions (cf Shepard, 2001a; 2001b; Vickers, 2001). This assumption means that the range of permissible transformations is limited to those that can be physically realised. It suggests that perceived symmetries are likely to facilitate the translation of seen structure into overt action. This assumption also provides an interpretation of the otherwise nebulous concept of 'perceived organisation'. According to this view, perceived organisation corresponds to the trajectories of those transformations that maximise the degree of generalised self-similarity in a representation and minimise the match between the generated representation and the presented image. That is, what we experience as a (non-visible) 'link' between one set of image elements and another corresponds to the minimum path that a physical action would follow in bringing the first set of elements into the closest correspondence with the second set.

A.3.   General properties of the generative transformational approach as a theory of visual perception

The applicability of the GT approach to the perceptual aspects of display design ultimately depends upon the adequacy of the GT approach as a theory of visual perception. As indicated earlier, a summary evaluation of the GT theory is naturally concerned with the dependence of the theory on information about relative position and the importance in the theory of invariance or symmetry under transformation.

A.3.1   The importance of nearest neighbour relations for visual perception.

Despite the advantages of NNA, there is little explicit recognition in studies of visual perception that the statistical properties of spatial point processes have been extensively analysed in a wide variety of other contexts. These include ecology, geography and geophysics, as well as geometric probability and spatial statistics (e.g., Cressie, 1993; Upton & Fingleton, 1985).

Relation to neurophysiological findings.
A possible reason for the neglect of NNs may be that the implications of NNA are difficult to reconcile with neurophysiological approaches based solely on classical receptive field (CRF) architectures. If CRFs correspond to structures defined in absolute spatial terms, and are independent, they should be associated with similar responses whenever those structures are present and independently of contextual information. In contrast, because NNA is based on relations among array elements, NNA predicts that responses should depend on relative, rather than absolute distances, and should be influenced by the distribution and density of *all* array elements.

Nevertheless, there are several recent neurophysiological findings that are consistent with the implications of NNA. For example, Motter & Belky (1998) found that target detection occurred only within a restricted area, determined by element density, and concluded that attention operates within an area having a radius of twice the average NN distance. Meanwhile, Brady et al. (1997) and Bex & Dakin (2003) showed that the visual system is sensitive to motion information at widely separate spatial frequencies and over a range of spatial scales. Similarly, Dakin & Herbert (1998) found that the spatial integration region for the perception of reflective symmetry varied inversely with peak spatial frequency. Such scale-invariant properties correspond well with recent evidence that element density is the property that the visual system uses to implement scale invariance in the perception of symmetry and Glass pattern structure (e.g., Rainville & Kingdom, 2002). Both scale-invariance and the determination of perception by element density are central implications of NNA.

Relation to psychological findings.
The importance of NN relations follows from the fact that NNs are concerned with relative distances and, in consequence, that NN distributions have certain characteristics. In consequence, an NNA-based approach can provide a resolution and explanation for certain problems and findings, common to the perception of structure, motion and depth.

The correspondence problem.
For example, the use of well-populated random dot arrays in experiments on visual perception has highlighted a general, so-called *correspondence problem*, common to the perception of structure, motion and depth. If a single element is displaced, from one frame to the next, by regular increments in a specific direction, within a background of elements that are distributed randomly and independently in successive frames, then it is possible to detect the constrained motion of the single element. However, because each element in one frame could logically be paired with any element in the succeeding frame, there are $n!$ possible correspondences for the visual system to consider. A similar computational problem arises with the detection of structure in Glass patterns (Glass, 1969) and with the matching of stimulus elements in the two halves of a pair of random dot stereograms (Palmer, 1999).

NNA deals with sets of (least) distances between pairs of points, the members of which can belong to a single array or to two spatially or temporally distinct arrays. Despite its simplicity, this property has important consequences. For example, NNA does not consider interactions among three or more sets of points. This agrees with evidence that the visual system does not require such information and does not process it (e.g., Todd, 1994; Williams & Sekuler, 1984). A second consequence is that the same processing can be applied to a single array, or two

successive or spatially distinct arrays. This means that, in principle, the perception of structure, motion and depth can all be explained by a single type of processing mechanism, and that similar information can give rise to any - or all – of these perceptions. A third consequence (most directly relevant to the correspondence problem) is that attention is restricted to a subset of all possible inter-element distances. Because each element has one NN, only n distances need to be considered – a significant reduction in computation.

Sensitivity to element density.
Experiments employing dot patterns have also produced the ubiquitous empirical finding that the perception of structure, motion and depth are all influenced by the density of pattern elements. Although intuitively unremarkable, this commonplace result represents something of a challenge for theory.

A second characteristic of NNA allows it to account for this finding and to differentiate between two major classes of explanation: one in terms of scale-bound mechanisms that respond on the basis of absolute size or a fixed spatial frequency; and a (less popular) alternative, based on relative distance. A critical instrument in this differentiation is the fact that the distribution of all inter-element distances in a random array has very different properties from that of NN distances.

As shown by Diggle (1983), the distribution of all inter-element distances for a random pattern is approximately normal. Importantly, the probability distribution function has no density parameter, so that the mean and all characteristics of the distribution remain the same, no matter how many elements there are. This means, for example, that any perceptual process that is potentially influenced by all inter-element distances (such as an array of overlapping motion detectors, each tuned to motion over a different absolute distance), should respond in much the same way, irrespective of element density.

In contrast, NN distances conform to a distribution, of which the mean and variance are specified by element density. In contrast to a scale-bound mechanism based on absolute distance, such a representation of stimulus information appears to be appropriately sensitive to variations in element density.

Sensitivity to clustering and symmetries.

Within the GT approach, differences between the distribution of NN distances and that of all inter-element distances provide a way of detecting the presence of constraint in an array of elements through a process of signal/noise differentiation, implemented in a sequential sampling decision mechanism of the kind described by Vickers and Lee (1998; 2000).

For example, on an approach based on CRF architecture, a possible explanation for seeing particular elements as clustered together, and for the number of clusters seen, is that all dots within a fixed distance from each other are seen as linked. This predicts that the number of clusters detected should increase as a function of the number of inter-element distances, $n(n-1)$, when the number of elements, n, is increased. Conversely, the number of clusters detected

should halve when the scaling of an element array is doubled. An alternative explanation is that perceived links correspond to NN links, and hence depend on relative distance. This predicts that the number of clusters detected should increase as a linear function of the number of NN distances, n, when the number of dots is increased. However, the number of clusters detected should remain the same when the scaling of an element array is doubled.

In agreement with the GT approach, Vickers, Preiss and Hughes (submitted) found that both the number of links and the number of clusters detected by subjects in random element arrays increased, as predicted, as a linear function of the number of elements in the array.

Structure in a visual array can also result from uniform transformations applied to all elements of the array. For example, Glass patterns are produced by superimposing a transformed copy of an array of randomly positioned elements (usually dots) on the original array. Marroquin patterns (Marroquin, 1976; see also Earle, 1991) are produced by superimposing a transformed copy of a regular array (such as a lattice of dots) on the original.

A second possible reason that no systematic programme of research into the role of NNs has been undertaken is that several researchers (e.g., Dakin, 1997; Maloney, Mitchison, & Barlow, 1987) have argued (mistakenly) that the perception of structure, despite the presence of non-corresponding NNs, shows that an NN mechanism cannot account for Glass pattern perception. However, the distribution of NN distances for corresponding elements has a different mean and variance to that for non-corresponding dots, and cumulative statistics have been developed (Vickers, 2002), that make possible the reliable differentiation of sampled distances as arising from one or the other distribution, even when several non-corresponding distances intervene. As a result, the GT approach is capable of accounting, at a qualitative level at least, for the observed effects of variations in noise, in element density, and in the step size of the transformations used to produce Glass patterns. Meanwhile, in the case of Marroquin patterns, periodic structure is revealed in the distributions of kth-order NN distances as ascending orders of k are considered.

Finally, an important class of pattern, generated by the same type of transformation process, has been investigated independently under the label of 'mirror' or 'reflective' symmetry. As recently shown by Rainville & Kingdom (2002), the region of maximal sensitivity to reflective symmetry varies with element density, as predicted by an NN approach.

Effects of boundary shape.
A further, general factor that has been little studied, but that has been shown to affect performance, is the shape of the boundary enclosing a visual display (Dakin & Bex, 2002).

If the perception of structure is thought of as a process of signal/noise differentiation, as proposed by the GT approach, then it would be predicted that boundary shape would have some effect on perception. The distribution of all inter-element distances is influenced by whether the elements are enclosed in a regular polygonal, a circular, or a rectangular area (Sheng, 1985). In the case of a polygonal boundary, the mean of the distribution depends on the number of sides, and, in the case of a rectangular boundary, the mean depends on the

height/width ratio (Lazoff & Sherman, 1994). For example, an elongated rectangle makes possible greater inter-element distances than a square of the same area.

Because NN distances are restricted (by definition) to elements that are in close proximity, their distribution is not sensitive to the overall shape of an enclosing boundary. However, corrections need to be made to allow for the effects of proximity to the boundary. As a result of the combined effects of boundary shape and perimeter on the distinguishability of the distributions of NN and of all inter-element distances, some effect of the shape of the enclosing boundary is predicted on perceptual performance.

A.3.2   The importance of symmetry and transformations for visual perception.

Symmetry.
Symmetry is defined as invariance under transformation, and most forms of structure can be regarded as some form of symmetry. Because the GT approach conceives the visual system as actively searching for symmetries (including partial and probabilistic mappings), it is likely, a priori, to have quite general applicability to visual perception.

As mentioned earlier, geometric approaches to visual perception focus on invariants (i.e., symmetries) in reflected images that are determined by relations between a light source, an object or scene and an observer. Such approaches have produced an extensive literature, that is typified by the so-called ecological approach to visual perception pioneered by Gibson (1966; 1979) and is well represented by recent studies by Wagemans, Van Gool, Lamote, & Foster (2000) and Cutting & Readinger (2002).

A distinguishing feature of the GT approach is that it permits a distinction between the above kind of optically determined structure and what might be termed *intrinsic* structure, that is due to the operation of non-optical constraints, such as forces of attraction and repulsion, between the elements of an array. Most geometrical approaches to visual perception are concerned with invariants associated with optically determined relationships. However, the process of perceptual organisation is concerned primarily with the detection of intrinsic structure, as illustrated by the examples, cited in the previous section, of clustering and regularity, Glass patterns, symmetry, and periodic patterns. An advantage of the GT approach outlined above is that it permits an objective (and ecologically grounded) characterisation of this kind of structure.

Transformations.
The central role of transformational processes in visual perception and cognition is also well established (e.g., Dodwell, 1983; Hahn, Chater, & Richardson, 2003; Hoffman, 1984; Leyton, 1992; Palmer, 1991; 1999; Shepard, 1994). However, previous transformational approaches have consisted of representational hypotheses rather than models of the perceptual processes. That is, they have been restricted to correlating the perceived organisation in an image with some objective measure of the geometrical characteristics of the image. In contrast, the GT approach is implemented in a computer model that also attempts to specify the process by which the relevant image characteristics are selected and extracted by the visual system as well as the process by which these characteristics select the transformations that maximise generalised self-similarity while minimising the difference between the generated representation and the current image input.

Vickers (2002) has summarised the properties of an earlier version of this GT model. The model is effective in identifying transformational structure in multi-element arrays, such as Glass and Marroquin patterns, irrespective of the particular transformation used to generate them. It is highly effective in identifying most - perhaps all - kinds of regularity in such arrays,

even when this structure is partially obscured by random elements in addition to, or instead of, the structured elements. It is qualitatively consistent with the general features of performance in the perception of visual structure, namely: scale invariance, sensitivity to element density, resistance to noise, sensitivity to boundary shape, and insensitivity to the order in which an array is scanned. The GT model can also be extended to account for the perception of fractal structure and the perception of shape and orientation in depth.

In addition to its account of perceptual processes, the GT approach may have some relevance for accounts of the relationship between perception and action. As mentioned earlier, the hypothesised transformational processes are assumed to have evolved from internal directions for guiding overt manipulative actions. In line with this, some researchers have suggested that the mental rotation of stimuli in experiments by Shepard and others (e.g., Shepard & Cooper, 1982) is closely associated with pre-motor processes (e.g., Kosslyn, 1994b). For example, Wohlschläger and Wohlschläger (1998) found that the making of rotational hand movements interfered with simultaneously executed mental object rotation, but only if the axes of rotation coincided. On this basis, Wohlschläger (2001) suggested that mental rotation is an imagined (covert) action, rather than a pure visual-spatial imagery task. Consistent with this view, these authors showed that the mere planning of hand movements interfered with mental object rotation.

A.3.3 Relation of GT approach to established theoretical approaches to visual perception.

The GT approach focusses on invariant relations between stimulus elements that are diagnostic of non-optical constraints, and so is complementary to geometrical approaches that focus on projective invariants. That is, the GT approach assumed that, like optical structure, the visual perception of intrinsic structure has a strong ecological basis.

Although a useful heuristic, the optimisation assumption underlying cognitive approaches faces difficulties in relating the optimised quantity (e.g., simplicity or likelihood) to measurable characteristics of visual stimuli, and realistic optimisation tasks present severe computational difficulties. The GT approach provides an objective procedure for stimulus analysis, while locally-focussed processes that use NN information depend linearly on the number of dots, and allow the system to produce near-optimal (least-distance) solutions at a feasible computational cost.

As noted, the NNA approach is difficult to reconcile with neurophysiological approaches based on CRF architectures. However, the relational perspective of NNA may provide a fruitful conceptual framework, consistent with recent neurophysiological work, which is based on evidence for much wider interconnection among the elements of a visual field than previously assumed, and which emphasises receptor field plasticity, context effects and normalisation by element density.

Psychological Implications for
Submarine Display Design

Matthew Dry, Michael Lee, Doug Vickers and Sam Huf

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19. ABSTRACT This paper addresses a number of psychological issues pertaining to display design. We review the literature comparing 3-D and 2-D displays and evaluate the findings in terms of sub-surface environments. In addition to the specific problem of display dimensionality this paper outlines a number of perceptual, cognitive and ecological factors that are relevant to display design for submarine environments. The Generative Transformational approach to visual perception is outlined and the relevance of transformational theory to display design is discussed. The paper also discusses a number of practical and theoretical factors relevant to empirical assessment of display utility and outlines three key areas for future research – representing uncertainty, using a cognitive model of human decision making, and conveying affective information - that have the potential to uncover novel theoretical developments and new technologies.